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Systemic risk in the global water input-output network

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ABSTRACT

The issue of water access and security has been emphasized in the recent policy debate on sustainable development (Sustainable Development Goal No. 6) and adaptation to climate change (CoP21 in Paris, 2015). This study provides new evidence about the Blue Virtual Water Input-Output Network. The main novelty of our approach is the combination of Structural Decomposition Analysis (SDA) with Network Theory. SDA reveals that size-related, technological and structural components have contributed substantially to changes in virtual water use. Network analysis offers new insights about the vulnerability of the system to shocks through trade links across country-sector pairs. Our analysis highlights a possible trade-off in the increasing importance of virtual water trade: the efficiency improvement in granting access to virtual water might come at the cost of increasing systemic vulnerability.

Overall, the great unbalance between water availability and usage combined with rigidity of global consumption and production networks and the risk of cascade effects imply increasing vulnerability of the virtual water network to shocks propagation.

1. Introduction

Global production chains virtually transfer large amounts of water resources from areas of production to far consumption regions, a phenomenon that has been named 'the globalization of water' [1], that is especially important for food security [2–4], conflicts for water [5] and overpopulation [6]. The capacity to engage in trade enables water-scarce countries to achieve food security and, more generally, to satisfy their demand for water-intensive products. The quantification and assessment of Virtual Water (*VW*) and the evaluation of the vulnerability of the *VW* network are particularly relevant as climate change and other exogenous shocks are likely to alter the geographical distribution of water availability and to increase the exposure to systemic risk of water misallocation [7]. The two main methodological approaches used in the literature to analyse Virtual Water Trade (*VWT*) are Input-Output (IO) Analysis and Network Theory.

IO tables express the monetary value of economic transactions occurring across sectors of an economy to account for sectoral interdependencies in the economic system. In the vast literature of environmentally extended input output analysis, the attention has been directed towards the attribution of the responsibility to producers and consumers for the exploitation of natural resources and the release of pollutants, by computing the net balance of pollution and of resource 'embodied' in traded goods. IO models allow to identify

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and quantifying both direct and indirect water use throughout the whole supply chain. Previous studies on water – related to international trade – considered both single-region IO data [8–10], sub-national multi-region IO data [11–13] and global Multi-Region IO (MRIO) data [14–17]. Based on IO analysis, the literature has developed a variety of Structural Decomposition Analysis (SDA)[1] in order to unravel and quantify the main drivers of change in pollution or in resource and water use. There are several examples of SDA of energy use [21,22], emissions [23,24] or water use [25,26] in a specific region or macro-area, with mixed results depending on the period, the environmental dimension that is considered and the countries and sectors included in the analysis.

On the other hand, Network Theory has been extensively used to analyse bilateral trade flows [27] because it enables to find non-local interdependencies among nodes (country-sector pairs in our case) involved in the international trade system and to capture useful information on the topology of exchanges. Network Theory is particularly suitable to deal with economic complexity, where hierarchies of economic sub-systems and the synergistic interactions between sub-systems can be detected [28]. Network analysis is a powerful tool to analyse complex influences of social and ecological structures (i.e., multiplex) on community and household dynamics [29].[2]

Neoclassical macroeconomic theory got rid of the possibility of cascade effects, based on the alleged diversification argument [30]. However, recent contributions showed that the interconnections between different firms and sectors play a key role in the propagation of idiosyncratic shocks throughout the economy [27]. A number of papers applied network analysis to study Virtual Water Trade as a global network by unveiling the main characteristics of its topological structure [2,31,32], as well as its geographical [33] and temporal evolution [34,35]. They main findings are that: i. The total volume of virtual water trade is likely to shrink as a consequence of climate change due to increasing crop prices; ii. International trade in food-related commodities has contributed to substantial savings of global water resources over time [7]; and iii. That the topology of exchanges is becoming denser over time as a consequence of globalisation. Following recent studies that integrate information provided by IO tables with Network indexes [27,36,37], we extend this approach to analyse the relation between global supply chains and water resources. The global *VWT* system is both interconnected and interdependent, which poses a problem of network vulnerability to exogenous perturbations [38–40].

The novelty introduced by the present study is the combination of the SDA with Network measures of systematic vulnerability to exogenous supply-shocks. Our approach proposes a multi-faced framework of investigation that is suitable for those resources, such as water, for which a price mechanism for the allocation of the resource is weak or absent, and the resource is not directly traded but it is virtually embodied in the exchanged goods. The use of IO allows to calculate the overall requirements of a resource and to identify the geographical origin of the resource. Network tools allow to study the systemic structure and the evolution of the network to unravel potential vulnerabilities in the exploitation and allocation of a resource.

The current study goes beyond previous contributions because we ground our analysis on inter-sectoral (virtual water) trade and not simply on final consumption. This step is essential to understand whether the current global supply-chain of virtual water is vulnerable to external shocks and whether the evolution of international trade is yielding riskier systems of *VW* exchanges. In particular: (*i*) we take into account the heterogeneous sectoral composition of each country, (*ii*) we assess the evolution of blue water use and the key drivers of its evolution, and (*iii*) we evaluate how the process of globalisation (increasing international trade) could affect the stability of the Blue VW IO Network (*BVWION*) via sectoral-level shocks.

The paper is organised as follows: Section 2 describes the World Input Output Database (WIOD) and introduces the main concepts. Section 3 explains the Input-Output methodology, while Section 4 discusses the drivers of blue water use by means of a Structural Decomposition Analysis (SDA). Section 5 introduces the network methodology and the fundamental topological properties of the global virtual water trade network. Section 6 discusses the methodological implications from the combination of SDA and Network theory. Finally, Section 7 summarizes the main results and identifies open issues for further research.

2. Data and definitions

The World Input Output Database (WIOD)[3] provides data on world inter-industry monetary flows of intermediate and final goods. The database includes 40 countries[4] which account for approximately 85% of world GDP and for approximately 70% of global Blue Water use.[5] Data (including Blue Water direct use, in m^3) are presented with a breakdown of 35 sectors for each country and vary in time.[6]

Before moving to our set of empirical applications, it is useful to discuss the most common definitions of Virtual Water present in the existing literature. Virtual Water[7] refers to the quantity of water 'embodied' in traded goods within and across national borders [44] including both direct and indirect uses along the whole supply chain [45].[8]

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1 See Refs. [18,19], and [20] for overviews of the literature.

2 In our paper we do not develop a multiplex analysis due to the high number of sector/country pairs involved but we decided to focus on directed and weighted network of VWT. Further research is needed to gain additional insights from multiplex network analysis in the context of world input output relationships of embodied water.

3 World Input Output Database, http://www.wiod.org, updated to 2013. WIOD is composed by a set of harmonized supply and use tables and symmetric I-O tables, valued at current and previous year's prices. For a description of alternative IO databases see Ref. [41].

4 Country coverage: 40 countries including EU27 Member States plus 13 non-EU countries (Australia, Brazil, Canada, China, India, Indonesia, Japan, South Korea, Mexico, Russia, Taiwan, Turkey, and the US) and the remaining regions of the world aggregated into a single region RoW (Rest of the World).

5 See http://waterfootprint.org/en/resources/water-footprint-statistics/for country level statistics.

6 See http://www.wiod.org/database/eas13 for a detailed description of the data sources used to estimate sector-country-year specific Blue Water direct use.

7 See Refs. [42] and [43] for a review of the literature on *VW* concept.

8 The sum of direct and indirect water use coefficients returns a vector of total water demand multipliers, equivalent to the virtual water content in m^3/\$. Details on the computation of Virtual Water based on input output analysis are discussed in section 3.

Blue water (*BW*) refers to the consumptive use of ground or surface water. The supply of blue water is costly, because it requires a specific infrastructure. Blue water is mobile, can be abstracted, pumped, stored, treated, distributed, collected, and recycled, thus each m^3 saved can be directed toward alternative uses by production activities and households. Here we consider renewable freshwater, then any quantity used in a year is available again the subsequent year.

For sake of brevity, we compare the results at the global level with those derived from a selection of countries: i. Developed countries (EU, US, Canada, Australia, and Japan, labelled as DEV) and emerging countries (India, China, Russia, and Brazil, labelled as LDC) countries. These selected countries cover together about the 50% of global GDP (source: World Bank) and about the 57% percent of total blue water direct use (source: WIOD) in 2009. The selection of countries includes both high-income and emerging countries which allows to compare the drivers of changes in water demand across rather heterogeneous regions.[9] Moreover, for illustrative purposes, we aggregate the 35 industries in four macro sectors: the Agriculture, Hunting, Forestry and Fishing (*AtB*) together with the Food and Beverage (*Fb*) that we call *AFF*, the Electric, Gas and Water supply (*EGW*), the Chemical, Textile, Pulp, Paper, and Metallic Products (*DUS*), and the remaining are pooled together because of their very small direct use of water (OTH).[10]

Table 1 compares the total amount of water used both in absolute level and per capita. Given the stability of the distribution and of the ranking across countries – in terms of water use – during the considered time span, we present the amount of Blue Water use in years 1995 and 2009.[11] There are three facts that emerge from the data reported by Table 1:

1. There is an uneven distribution of direct water use both in terms of absolute level and per capita. The first three countries in the ranking, China, India, and the US, were responsible of about 41% (39%) of the total amount of blue water use worldwide, in 2009 (1995);
2. The ranking of countries in terms of absolute water use and per capita water use remains rather stable over the time span 1995–2009;
3. Blue water use (absolute and per capita) has increased substantially over time.

In what follows we assess the role played by inter-sectoral exchanges, international trade, technological shifts and change in size and composition of final demand in driving these aggregate figures.

2.1. The input-output system as a network

The *MRIO* model offers a variety of tools to ascertain several features of economic activity both at local and global level, such as: (i) tracing the trade structure between countries and the related impacts on economic systems, environmental pressures, and society, (ii) identifying and quantifying the key drivers that cause changes over time in economic, social or environmental variables, and (iii) evaluating the economic and environmental consequences due to (short-run) exogenous shocks. Even though they were designed to keep track of inter-industry links, the IO systems have been extensively applied in the field of network science. The MRIO system can be viewed as an interdependent complex network, where nodes are thought as country-sector pairs and edges are the monetary flows related to the exchange of goods and services between industries. More precisely, in our analysis the MRIO system measures inter-industry and inter-country of water embodied in the production of goods and services.

We consider the global MRIO system as a world input-output network, in order to assess the evolution of *VWT* and the vulnerability of the system to (potential) exogenous shocks. Research on input-output links as a network, though relatively new, is expanding rapidly. The recent bulk of literature in economics stresses that the structure of this production network is key in determining whether and how microeconomic shocks that affect only a particular sector-country can propagate throughout the economy yielding aggregate outcomes. The study of the mechanisms through which shocks diffuse in economic and ecological systems is of a foremost importance to devise policy measures that can help water management strategies. Whereas most papers have analysed the mechanisms of contagion in financial [46,47] and economic networks [39,40], much less is known about how the topology of interdependencies between the sectors and countries could affect the access to and the distribution of natural resources. An interesting feature, that was found in many networks, is the presence of a highly heterogeneous structure, with degree distributions characterized by large variability and heavy tails. This feature, in a context of inter-sectoral input-output linkages, has proven to be fundamental to understand how microeconomic idiosyncratic shocks may lead to aggregate effects [27]. Indeed, higher-order interconnections capture the possibility of cascade effects whereby local shocks propagate to the rest of the economy [40].

Differently from previous studies [2,34,35], we analyse network statistics and we evaluate time series of network properties considering the *country-sector pair* as the node and the flow of *VW* as the edge. On the one hand, MRIO allows a more refined approach with respect to simple trade links since it includes intermediate economic sectors, then allowing to recover the *VW* through the overall supply chain of production and consumption. Moreover, differently from most of the previous studies that focus on agricultural and food products, we consider all commodities, including many water-intensive industrial products such as energy, paper, and chemical products. The consideration of all products within a MRIO framework comes at the cost of dealing with a rather crude sectoral aggregation for what concerns many water-intensive sectors such as the agricultural and food sectors that, in our analysis, are not broken down into detailed commodities with heterogeneous water footprints. Another drawback of using world Input Output data is that they are not the result of a direct data collection process as trade statistics; rather, they are the result of modelling exercises that aim at

[9] A complete list of results for all countries in WIOD are available in Appendix B.

[10] See Table B6 for the list of all 35 industries present in WIOD.

[11] These volumes are provided by the WIOD database, Release 2013, http://www.wiod.org/database/eas13.

Table 1
Comparison between the top 7 countries in 1995 and 2009 of: total (Km^3) and per capita ($1000\ m^3$) blue water use at country level (in brackets the share with respect to global values).

Blue Water Statistics								
Rank	km^3 1995		km^3 2009		$1000m^3$ per capita 1995		$1000m^3$ per capita 2009	
1	India	242 (15.96%)	China	315 (16.22%)	Canada	2.91	Canada	2.76
2	China	176 (11.65%)	India	305 (15.71%)	Sweden	1.91	Sweden	1.75
3	USA	175 (11.57%)	USA	182 (9.39%)	Austria	1.17	Austria	1.21
4	Canada	86 (5.66%)	Brazil	113 (5.80%)	Australia	0.88	Australia	0.63
5	Brazil	75 (4.96%)	Canada	93 (4.80%)	USA	0.66	Finland	0.61
6	Russia	57 (3.70%)	Russia	61 (3.15%)	Finland	0.65	USA	0.59
7	Japan	24 (1.63%)	Turkey	25 (1.32%)	Greece	0.46	Brazil	0.58

harmonizing country-level Input Output tables with international trade statistics.

Our study aims at integrating the results from SDA with the study of the topology of the VW network in order to provide a rich framework of analysis that is able to provide a qualitative evaluation of the implications of trade and water-management policies in terms of *VW*. SDA quantifies the impact of the main drivers over time, while Network theory assesses the vulnerability of the system to exogenous shocks diffused through trade. To sum up, we may say that demand-level shocks can be evaluated by considering their impact on the need for Virtual Water by using the results coming from the SDA, while the effect of supply-side shocks can be evaluated by considering the topology of the VW network as described by network statistics.

3. BVWION: international trade balances

Global trade involves, to a different degree, all countries in the world, each of which is characterized by a technology of production given by the different mix of intermediate inputs. A natural approach to deal with this framework is the application of a Global MRIO Model [48] in which there are R regions (countries in our case) composed by the same number (S) of sectors. The matrix of intermediate exchanges is composed by $(R{\cdot}S)^2$ elements. This approach allows to exploit both information about the exchange within a country from sector i to sector j (z_{ij}^{RR}) and international trade from country B to country M (z_{ij}^{BM}), with possibly $i=j$.[12] In what follows, we describe the logic of the MRIO model, the notation and the main equations that will be used in Section 4.

Let assume, without loss of generality,[13] that the world is composed by two countries (M,B) with two sectors each (i,j). The aggregate world IO table Z of intermediate exchanges has, on the diagonal, the square matrices Z^{MM} and Z^{BB} which represent domestic inter-industry flows, while off-diagonal matrices Z^{MB} and Z^{BM} record the interindustry flows across countries (i.e., international trade in intermediates). In particular, each element z_{ij} indicates the monetary value of intermediate exchange from sector i to sector j, that is the element z_{ij}^{BM} is the monetary value of trade from sector i of country B to sector j of country M.

$$\begin{pmatrix} z_{ii}^{BB} & z_{ij}^{BB} & z_{ii}^{BM} & z_{ij}^{BM} \\ z_{ji}^{BB} & z_{jj}^{BB} & z_{ji}^{BM} & z_{jj}^{BM} \\ z_{ii}^{MB} & z_{ij}^{MB} & z_{ii}^{MM} & z_{ij}^{MM} \\ z_{ji}^{MB} & z_{jj}^{MB} & z_{ji}^{MM} & z_{jj}^{MM} \end{pmatrix} \tag{1}$$

Let x be the vector of total output, given by the row sum of intermediate exchanges (Z) plus the matrix of final demand (F) which includes domestic consumption and international trade of final goods. It is possible to split the system among different regions, hence also x is composed by x^B and x^M. The vector f of total final demand (row sum of F) is composed by domestic demand and exports. The matrix of technical coefficients (A) describes how much of the production of sectors of each row is required (directly) to produce one monetary unit of output of the sector in the column, that is $A = Z{\cdot}\hat{x}^{-1}$, where $\hat{x}$ is a diagonal matrix composed by the inverse of the elements in x (i.e, $\frac{1}{x_i}$).[14] Given that A has the same structure of Z, we distinguish the domestic matrix blocks A^{BB}, A^{MM}, and those that describe the international intermediate trade: A^{MB} and A^{BM}. The Leontief matrix L solves the linear system: $x = A{\cdot}x + f$, and it is thus given by $L = (I - A)^{-1}$. Each element l_{ij} of L indicates how much the monetary value of the production of sector j must increase (overall) given an unitary increase in the final demand of good i. Matrix L captures not only the direct links (A) but also the indirect ones. To compute the total use of water at the global level that is needed to satisfy final demand, we compute the vector water intensity (γ) as the element-by-element ratio between direct water use of each country-sector pair and the total monetary output of each country-sector pair. This vector describes the direct use of water for each sector-country (and year) pair needed to produce one monetary unit of output. Table B1 in Appendix B shows the value of direct water intensity γ for the four main macro-sectors (*AFF*, *EWG*, *DUS*, and *OTH*) and for both DEV and LDC countries. We observe a remarkable heterogeneity in water intensity both at cross-sectoral and cross-country levels. Even within the same macro-sector, we observe very large differences in direct water use per dollar of output. For example, in 2009 the water directly used to produce one dollar's worth of agriculture and food products was 61 times larger in India than in Japan.

[12] In our case, given the high level of aggregation, each sector is actually composed by several firms and sub-sectors. For this reason, we find positive (and large) values on the main diagonal.
[13] See Ref. [48] for a full description of the IO methodology.
[14] In matrix notation, the hat indicates the diagonal matrix.

Moreover, we also observe substantial changes in water intensity through time within the same sector and country. For example, the direct use of water in the *EWG* sector in Russia was 3.34 times larger in 1995 than in 2009.

Let w be the vector of total water use of each sector, then $\gamma = w \cdot \hat{x}^{-1}$. Total water requirements of each sector is then defined as:

$$\omega = \hat{\gamma} \cdot L \cdot f \tag{2}$$

Combining γ and L we define the matrix of the water use multipliers $\Theta = \hat{\gamma} \cdot L$. Each element θ_{ji} of the matrix Θ measures the overall water impact of an increase of final demand of one monetary unit (in one sector/country pair) for each sector in each region in the world.

3.1. VWT: evidence

In what follows, we show how international trade of intermediate and final goods and services, with the corresponding *VWT*, allows some country to indirectly use water coming from other countries. The two key sectors are *AFF* and *EWG* that cover around the 57% and the 40% of direct blue water use, respectively. We define the *VW* of export (Θ_{Exp}) and import (Θ_{Imp}) of country C of both intermediate and final goods, from which we derived the water trade balance $\Theta_{BAL} = \Theta_{Exp}$ - Θ_{Imp}, as:

$$\Theta_{Exp}^{C} = \sum_{k=1}^{R} \Theta_{CK} \cdot (f_K - f_{KC}) \tag{3}$$

$$\Theta_{Imp}^{C} = \sum_{k=1}^{R} \left(\tilde{\Theta}_K - \Theta_{CK}\right) \cdot f_{KC} \tag{4}$$

$$\tilde{\Theta}_K = \sum_{j=1}^{R} \Theta_{jK} \tag{5}$$

where f_{CC} is the domestic final demand, while f_{kC} represents the vector of export for final demand from country K to C, and f_K is the row sum of the matrix of final demand for each sector in country K. $\Theta_{CK} = L_{CK} \cdot \omega_C$ is the square sub-matrix which shows the Leontief inverse for country C, when it exports to K, multiplied by the vector of sectoral water use intensity of country C. Note that $\Theta_{CC} \cdot \sum_{K \neq C}^{N} f_K$ returns the water use in country C when producing goods and services for final use which are exported to all the other countries. Given $K \neq C$, it is possible to recover the water required in country C when producing the intermediate exports that are used abroad to produce final goods and services consumed by country K as $\Theta_{CK} \cdot \sum_{K \neq C}^{N} (f_K - f_{KC})$. We define a country C as a "water debtor" if $\Theta_{Imp,C} > \Theta_{Exp,C}$ [see e.g. Ref. [49], page 519].

An important conclusion from studies on *VW* trade is that, in many cases, international *VW* trade does not follow the spatial pattern

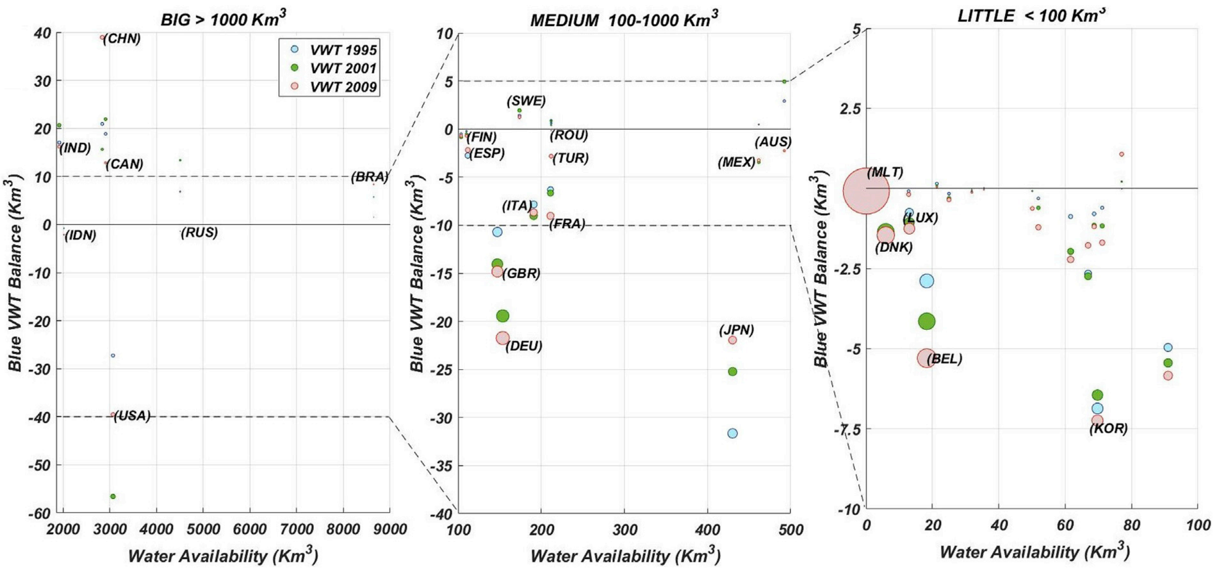

Fig. 1. Relation between Water Availability and net trade balance of *BVW* in 1995, 2001, and 2009. Points above zero stand for net exporter of Blue (virtual) water, while the water debtors lie below. BIG stands for water abundant countries (> 1000 km^3 of Wa), MEDIUM stands for countries endowed with an amount of renewable freshwater between 100 and 1000 km^3 and LITTLE are countries with less than 100 km^3 of Wa. Bubble size is proportional to the ratio – in absolute value – between the *BVWT* balance and the Wa of each country. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of fresh water resource availability [42]. Fig. 1 suggests that international trade has a high impact on the possibility of a country to face its domestic requirements by comparing the levels of VW trade balance and of water availability.[15] In fact, countries with the smallest value of water availability are also net debtors of virtual water while few big countries (e.g. China, India, and Canada) with large reserves of water are also net exporters of VW.[16] The findings of [49] are confirmed, with a progressive diversion of virtual water from the developing (China, India, and Brazil) to developed countries (see Table B2 in Appendix B). The main net importers are: the US (~ 720 Km^3), Japan (~ 380 Km^3), Germany (~ 300 Km^3), and Great Britain (~ 225 Km^3). Note that, once compared with water availability (Wa), there are only few countries with large water endowments (China, India, Canada, and Brazil) which cover the greatest part of the export of virtual water. Big countries are rather heterogeneous, some of them are net exporters: China (~ 400 Km^3), India (~ 310 Km^3), Canada (~ 275 Km^3), and Brazil (~ 100 Km^3); while the US and most European countries were net importers of *BVW*. Note that some results differ from the ones found in the literature. In particular, in our case the US is net importer of VW, while the Asian countries are mostly net exporters, the opposite of what is found in Refs. [2,32,34]. This divergence in results confirms that including more sectors than simply the agricultural one might unravel new dynamics in the international VWT. The case of Russia is particularly interesting. Russia was an important exporter in 2001 (+13 Km^3) but became a net importer (−1.4 Km^3) in 2009, although it is a water abundant country.

As it is well known in international trade theory (e.g., the Heckscher-Ohlin model of factor endowment), inasmuch as a country is less endowed with a production factor (e.g. water), it specializes in the production of commodities with little need of the scarce production factor and it imports commodities intensive in the scarce production factor. In the case of water, specialization according to the Heckscher-Ohlin would give rise to trade in virtual water. Here, it emerges a tendency of international trade to redistribute *VW* from water-abundant to water scarce countries (with the exception of the US). From a systemic point of view, these facts raise the question about the vulnerability of *VW* trade in case negative (climatic) shocks hit the main nodes of the virtual water network.

4. Structural decomposition analysis

As discussed in the previous section, trade in virtual water has increased substantially in recent years. The existing literature agrees that this dynamic has been driven by a variety of factors such as changes in ‘water efficiency’ (in terms of use of water per unit of production), structural change, composition of final demand and scale effects [14]. In this section we dig deeper into the drivers of virtual water by decomposing recent trends of virtual water in their various components. Structural decomposition analysis (SDA) is a particularly useful tool to evaluate the likely impact of demand-side change (and shocks) as it is based on the demand-driven Leontief model. We apply a simplified version of the SDA used by Ref. [24]. Differently from Ref. [24], we do not evaluate changes in environmental pressures embodied in export (either of final goods and services or of intermediates) but we evaluate directly the water required to satisfy the final demand of each country. This is particularly suitable for our purposes as we can capture the importance of the different driving forces of total *VW*. From a methodological viewpoint, SDA offers as static comparative analysis that allows to quantify the variation in water requirements as a consequence of a change in one component by keeping all the other components unchanged (i.e., *ceteris paribus* condition). Mathematical details about the decomposition are discussed in Appendix A. The relative change of total water use from time t to $t+1$, $\Delta w = (w_{t+1} - w_t)/w_t$, is a function of the following drivers, that are:

$$\Delta w = \Theta\left(IE, T, H, Q_{POP}, Q_C, Q_{cap}, D^*\right) \tag{6}$$

where the intensity effect (*IE*) refers to changes in water intensity coefficients (γ), T, and H represent the effects of trade and change in the sectoral composition of intermediate inputs, respectively, captured by the Leontief inverse in the MRIO model. The impact of final demand is decomposed into four components: impact of international trade (D^*), change in the product mix (Q_C), and change in consumption per capita (Q_{cap}) and population size (Q_{POP}). Fig. 2 shows the cumulative contribution to changes in water use of each component with respect to the water use in the base year (1995).

The water *IE* component describes the role played by changes in the vector of direct water use per unit of produced output. More specifically, this component describes how changes in *VW* in all countries affect the total water requirement of a specific country. Overall, improvements in water efficiency (reduction of γ, that is less water per unit of production) of production activities allowed to reduce world water use by about 90% over the period 1995–2009. The contribution of this component has been rather small in the first years of the series (1995–1999) and then accelerated substantially up to 2009.

The central panel of Fig. 2 shows in more details the impact on water use related to intermediate goods, that are T and H. The component H should be interpreted as the contribution to *VW* of changes in the technical coefficient matrix (i.e., mix of intermediate inputs) with no consideration of the geographical origin of intermediate inputs. A positive sign reveals a systematic increase in the relative importance of water-intensive sectors. Overall, this component has driven up the world water use by about 8% over the period

[15] As a proxy of Water Availability (Wa), we use the variable “Total Actual Renewable Water Resources” which shows the maximum theoretical yearly amount of renewable freshwater actually available for a country at a given moment. For a more in dept discussion see Ref. [44] (pag. 34) and [15]. Our proxy of water availability, that is not directly comparable in magnitude with our measure of Virtual Water, is the sum of internal renewable water resources (IRWR) and external actual renewable water resources (ERWR). In particular, the indicator is computed as the sum of total renewable surface water and total renewable groundwater, minus the possible overlap between the two resources. For more information refer to FAO AQUASTAT (http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en) and [44].

[16] The correlation coefficient between water availability and net VW balance (export minus import) is positive both when considering absolute values (72.4) and when considering per capita figures (68.9).

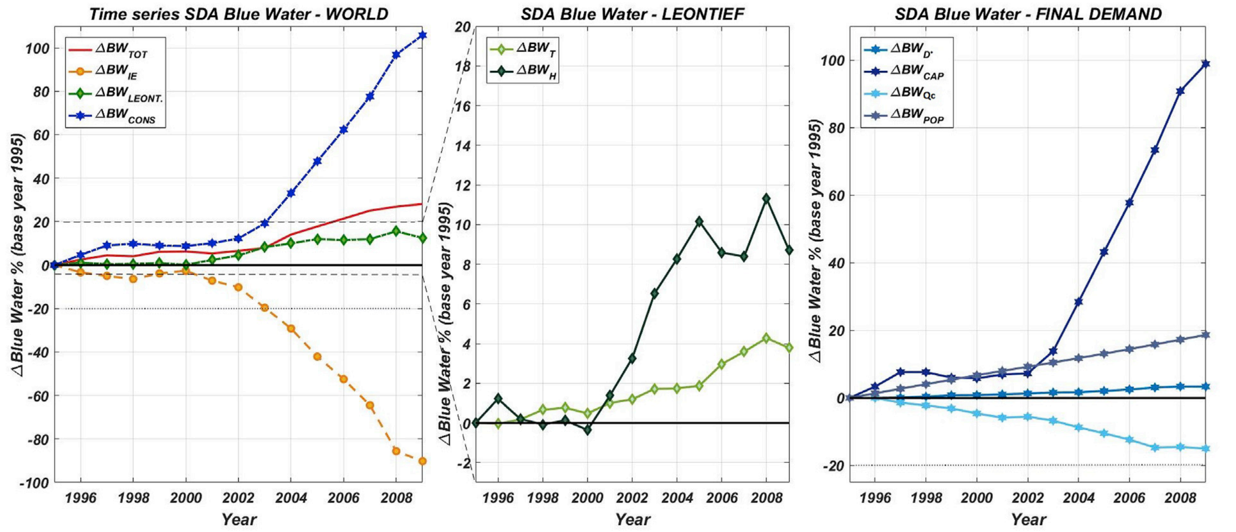

Fig. 2. World summary: time series (1995–2009) of the global SDA for the three main components: water efficiency (IE), technology of production (Leontief), and final demand (Cons), on the right. The central panel show the decomposition of the impact of intermediate good, based on trade (T) and production mix (H). The right panel shows the SDA of final demand for the four components: trade (D∗), consumption mix (Q_C), population and consumption per capita. The percentages show the cumulative effect with respect to the water use in the base year (1995).

1995–2009. The component *T* accounts for changes in the 'geographical' composition of the mix of intermediate inputs for a fixed average mix of intermediates (i.e., *H*). A positive sign should be interpreted as a systematic shift of the purchase of intermediates towards more water-intensive (in terms of average γ) countries. At the aggregate level, this component is very small (4%) and contributed positively to *VW*. Quite surprisingly, the composition of trade of intermediates has remained rather stable in the considered period, especially when compared to changes in production technology (*H*). Trade links seem to be persistent in time and are likely to be tightly connected to stable factors that determine trade patterns such as bilateral relationships between countries, comparative advantage, trade costs and factor endowment. This is particularly interesting as shocks in water availability, that might drastically reduce the supply of water-intensive goods of a specific country hit by the shock, are likely to influence the demand for water quite substantially due to the 'rigidity' of bilateral trade patterns.

The right panel of Fig. 2 shows in more details the impact on water use related to the four components of final demand. The first two components, Q_C and D^*, are the counterparts for final demand of the components *H* and *T*, respectively. The component Q_C quantifies the role played by changes in the product mix of final demand for a given level of final demand and for a given 'geographical' composition of final demand. We find a negative contribution of this component to total water demand, in the order of about 18% over the period 1995–2009. The role of changes in the 'geographical' distribution of final demand is described by the component D^*. Results for this component are very similar to the ones found for *T*. Changes in the geographical distribution of final demand contributes positively to the overall demand of virtual water, even though the effect is rather small (about 3.3%). The last two components refer to more aggregate driving forces, that are: changes in total final demand per capita (in real terms) and demographic growth. The role played by changes in Q_{cap}, which is strongly correlated with affluence, is very important. Final demand per capita is by far the biggest component that drives virtual water, accounting for the doubling of worldwide water use over the period 1995–2009. Population showed a further positive impact of about 20%.

4.1. Country level SDA

Results for single countries highlight a substantial degree of heterogeneity. Fig. 3 shows the results of *IE* for specific countries: developing (left panel) and developed (right panel).[17] Changes in water intensity contributed to an overall reduction in water for all countries except Japan but with heterogeneous magnitudes. The BRIC countries show a consistent reduction over time, with cumulative contribution that goes from −70% to almost −160%.[18] Russia showed a volatile pattern that might reflect its economic conditions. Indeed, during the economic crisis occurred in the period 1998–2000 we observe that water efficiency worsens due to economic and institutional disruptions. Instead, from the year 2000 onward, its γ coefficient decreased in correspondence of a period of fast economic

[17] Results for other countries in WIOD are not reported and remain available upon request.

[18] Note that in this case the percentage could be smaller than −100% because each variation is computed with respect to the previous year, and each year showed an increase in water use. An example might clarify: let assume that the water use is constant over time at 100 km^3, and assume that there are only two factors that influence water use: *x* and *y*. Let imagine that each year *x* would contribute – *ceteris paribus* – to an increase of 20 Km^3 that are exactly compensated by *y*. Then if we compute the cumulative variation, with respect to the value of the first year (100), we would obtain values smaller than −100% from the sixth year on (i.e., −120%) for the factor *y*.

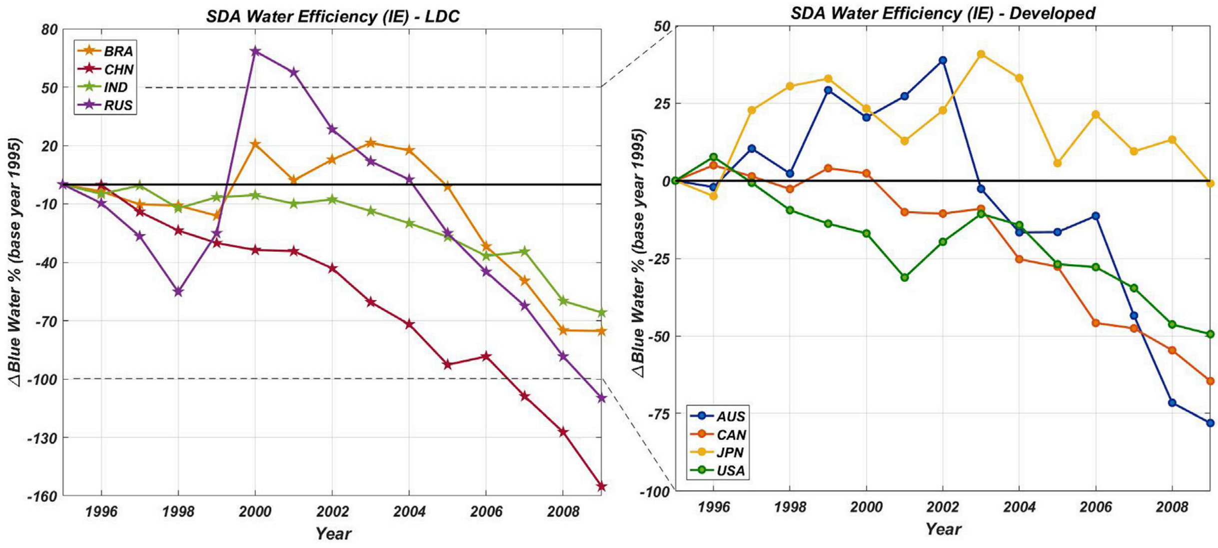

Fig. 3. Time series (1995–2009) of the water intensity (*IE*) component for a selection of developing (left) and developed (right) countries. The percentages show the cumulative effect with respect to the water use in the base year (1995).

recovery and political stability.[19] The US, Australia, and Canada show an overall reduction in the range between −50% and −70%.[20] Interestingly, while the overall cumulative trends go in the direction of a negative contribution (i.e., smaller water use) from γ, many years have been characterized by (even substantial) increases in average water use per unit of output.

Fig. 4 displays the H (right) and T (left) components for DEV (top) and LDC (bottom) countries, showing mixed outcomes. The production-mix contributed positively, in terms of VW, only for Brazil (∼ 8.5%) and China (∼ 20%) over the period 1995–2009. Interestingly, in case of Brazil the contribution of H had an inverted U-shape trend, while for China we estimate a steep increase starting form 2003, although anticipated and deep structural change shifting away from water-intensive agricultural sectors [51] but with higher use of the water-intensive EWG sector that superseded the savings from AFF (see Table B4). In the other cases, the sign was negative with a magnitude ∼ 15− 20% for India, Russia, and Canada, and of ∼ 5− 10% for Australia and the US, while basically no change is observed for Japan. Overall, the production technology has changed, in recent years, in the direction of requiring an increasing amount of virtual water (Fig. 2, central panel).

The effect of changing trade patterns in intermediate goods generates smaller variations with respect to the production-mix. Similarly to the 'water efficiency', trends are not systematically upward or downward. Looking at the overall 1995–2009 cumulative contribution of the T component, we observe that the major country that shifted its demand of intermediate inputs towards systematically more water intensive countries (in terms of average γ) is China, with an increase close to +20%. The contribution of this component is smaller than 10% for India, Brazil, Russia, and Canada, while it is negative and in the order of 5–10% percent for Japan and Australia. Although Japan is highly dependent on import for its food needs, it was able to reshape the import to a system of relations that reduced the VW associated to the trade of intermediate goods.

Finally, we consider the role played by final demand for both the DEV (Fig. 5) and LDC (Fig. 6) countries. This component is further decomposed into four components: D^* (top-left panel), Q_C (top-right panel), Q_{CAP} (bottom-left panel), and Q_{POP} (bottom-right panel). Starting from the consumption-mix (Q_C), we observe a general transition of final demand towards sectors with a systematically smaller water per dollar, the only exception being Japan and the US, for which basically no change is visible. In the latter case it seems surprising because after two decades of almost linear reduction, the US recover almost all the difference in only one year, in correspondence with the financial crisis of 2008–09. The component is particularly big in magnitude for China and India, for which changes in the sectoral composition of final demand contributed to a reduction of water of ∼ 40% over the whole time window. As highlighted in the recent literature [26,49] this evidence is linked to the relative decrease in the share of final demand directed to food products, which are particularly water-intensive.

Looking at the evidence for water use due to shift of trade (now of final goods) the evidence is mixed. China was the only big country that experienced a relevant increase (∼ +21%) in D^*, i.e. importing from more water-intensive countries (about the same contribution of factor T for the same country). For the other LDC the contribution of D^* is close to zero, while the contribution is slightly negative for all DEV (∼ –2.5%/–5%) except Canada (∼ +2.5%). These results are in line with the ones discussed for the component T, denoting a substantial rigidity of the geographical distribution of trade patterns.

[19] Russia was the biggest exporter of wheat worldwide in 2016, while in 1993 it was the biggest importer of wheat worldwide [4].

[20] The rather volatile trend of Australia in the early 2000s is likely to be related to the so-called *Millennium Drought* that hit the South-East of Australia in those years [50].

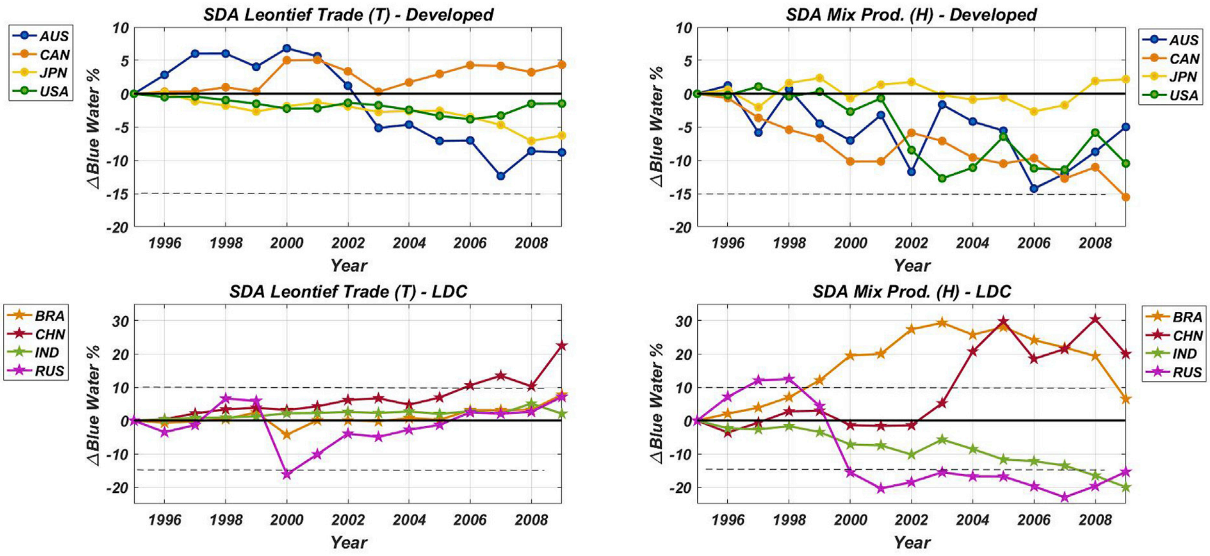

Fig. 4. Time series (1995–2009) of the SDA related to IO exchange: trade (*T*, left) and production-mix (*H*, right) components. Selection of countries: developing (bottom) and developed (top) countries. The percentages show the cumulative effect with respect to the water use in the base year (1995).

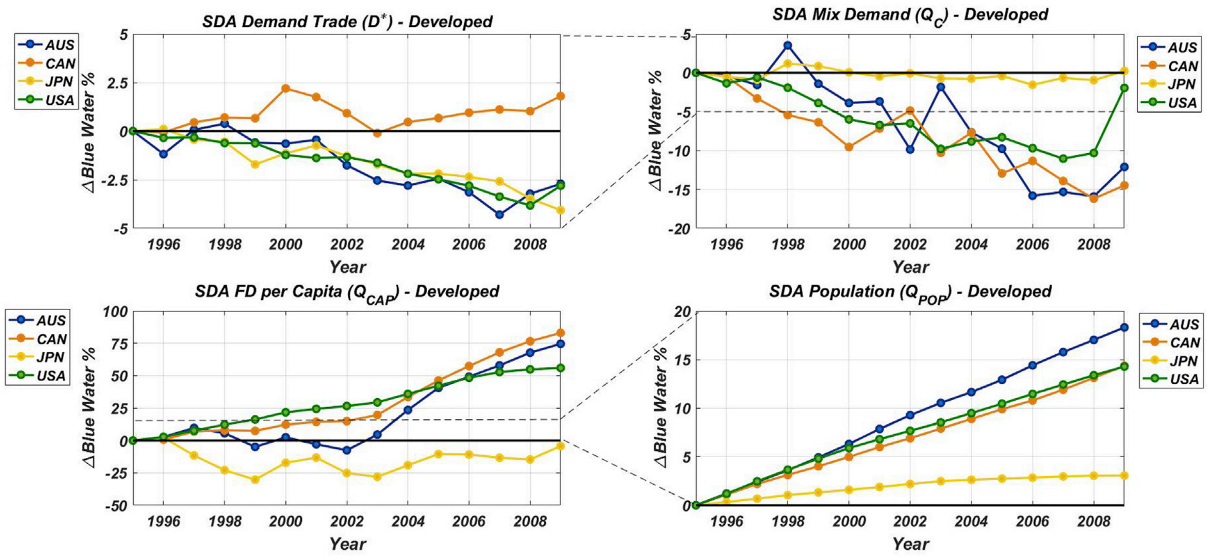

Fig. 5. Time series (1995–2009) of the SDA related to the four components of final demand – trade (top-left), consumption mix (top-right), consumption per capita (bottom-left), and population (bottom-right) – for developed countries. The percentages show the cumulative effect with respect to the water use in the base year (1995).

In line with previous findings [26], the consumption per capita (Q_{CAP}), that is strictly correlated to affluence (i.e., GDP per capita), is the main cause of increase of *VW* use. This effect was particularly important for LDC, from about +100% (Brazil) to a peak for China that almost tripled its *VW* with respect to 1995. In the DEV countries the increase was less than half ($\sim$ 50–75%) than LDC, and no change is observed for Japan. These differences reflect asymmetric macroeconomic growth across countries, with evidence of a substantial convergence of emerging countries towards high-income countries both in terms of affluence and in terms of water demand. On the other hand, the role of demography has been very stable over the period, contributing to steady increase in *VW*. The magnitude is of about 10–20% in each country, with the exception of Russia and Japan for which the contribution is negligible over the period 1995–2009.

To summarize, the structural decomposition has highlighted that while size-related components (population and affluence) and technological-structural components (water intensity and structure of final demand and intermediate inputs mix) have contributed substantially to changes in the demand for water, the geographical-related components (both in terms of final demand and intermediate

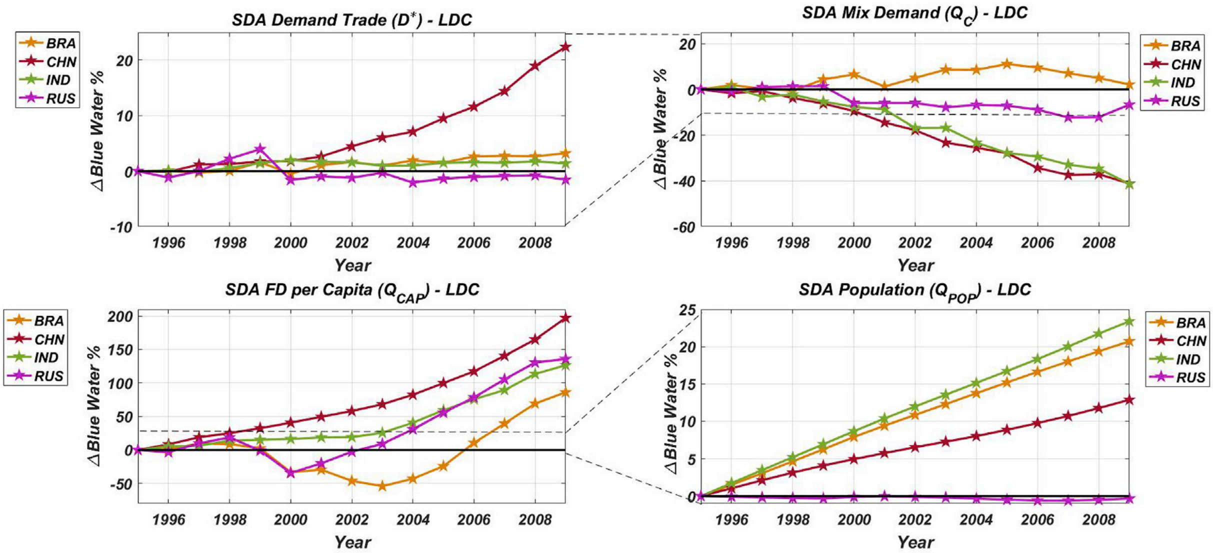

Fig. 6. Time series (1995–2009) of the SDA related to the four components of final demand – trade (top-left), consumption mix (top-right), consumption per capita (bottom-left), and population (bottom-right) – for developing countries. The percentages show the cumulative effect with respect to the water use in the base year (1995).

inputs) had very little influence on the demand for water, also because of the time-invariant nature of the factors that determine the specialization of countries (including water availability). This result, however, may suggest another possible implication: if the geographical structure of trade patterns was not responsive to differences in water endowment and efficiency across countries, what would happen in case of shocks to water availability that are likely to occur due to climate change? How would these shocks propagate across different countries and sectors and how vulnerable is the *VW* trade network? These questions will be the subject of Section 5.

4.2. Sectoral level SDA

To complete the evaluation of the driving forces of *VW*, we also provide evidence on the role of the driving forces broken down by sector. To the best of our knowledge, this is the first attempt to provide such a level of detail in the decomposition of water use. In our opinion these findings provide additional insights about the attribution of responsibility for the depletion of water resources, and open the way towards future research aiming at refining the scale of investigation (e.g., firm level) for two reasons: (i) avoiding aggregation bias and loss of information that affect macro-variables, and (ii) providing data and analyses at lower scale (i.e., regions) can be worth to guarantee a sustainable management of local resources, like water.

Fig. 7 shows the basic SDA – related to water efficiency, trade in intermediate inputs, and final demand – for four macro-sectors (*AFF*, *EWG*, *DUS*, and *OTH*). As expected the most relevant variation are reported only by the first two sectors, with only a slight contribution coming from *DUS*. For this reason, we will only shortly discuss the outcomes of *AFF* and *EWG*. The trends followed by water efficiency (left panel) and final demand (right panel) are similar for the two sectors. Surprisingly, the *EWG* (-50%) improved its water efficiency faster than *AFF* (-40%) in terms of direct use of water per dollar of sectoral output (i.e., γ). The global contribution to the increase of water from final demand is split almost equally between the two sectors ($\sim +50\%$ each). Interestingly, the trends related to the matrix of intermediate exchange show opposite signs: the *AFF* sector slightly decreased its use of water, while the *EWG* reported an increase of $\sim +15\%$. Overall, the two sectors contributed both to almost the same increase in the water use, of about +14.3% (*AFF*) and 12.5% (*EWG*) with respect to the amount of 1995.

Finally, Fig. 8 shows the complete SDA, for each macro-sector, with the cumulative variation in absolute terms (Km^3). In each case the most important driver is the level of consumption per capita. However, the magnitude of this component appears to be rather heterogeneous: *AFF* ~ 1000 Km^3, *EWG* ~ 500 Km^3, and *DUS* ~ 30 Km^3. For the three sectors, the trend accelerates steeply from the year 2003 onwards as a consequence of rapid economic growth. The other components of the demand seem negligible in each case, with few exceptions: Q_C in *AFF* contributed to a reduction of more than 250 Km^3 (~ –17% with respect to total *BW* in 1995), Q_{POP} in *AFF* was responsible of an increase of more than 180 Km^3 ($\sim +12\%$ with respect to total *BW* in 1995).

5. Network analysis of virtual water flows

Network analysis is particularly suitable to evaluate the short-term impact of supply-side shocks to the water system. Differently from SDA, that is based on the demand-driven Leontief model, network analysis evaluates the likely consequences of the collapse of one or more nodes of the network. When considering the network of virtual water flows, the collapse of a node is equivalent to assume that

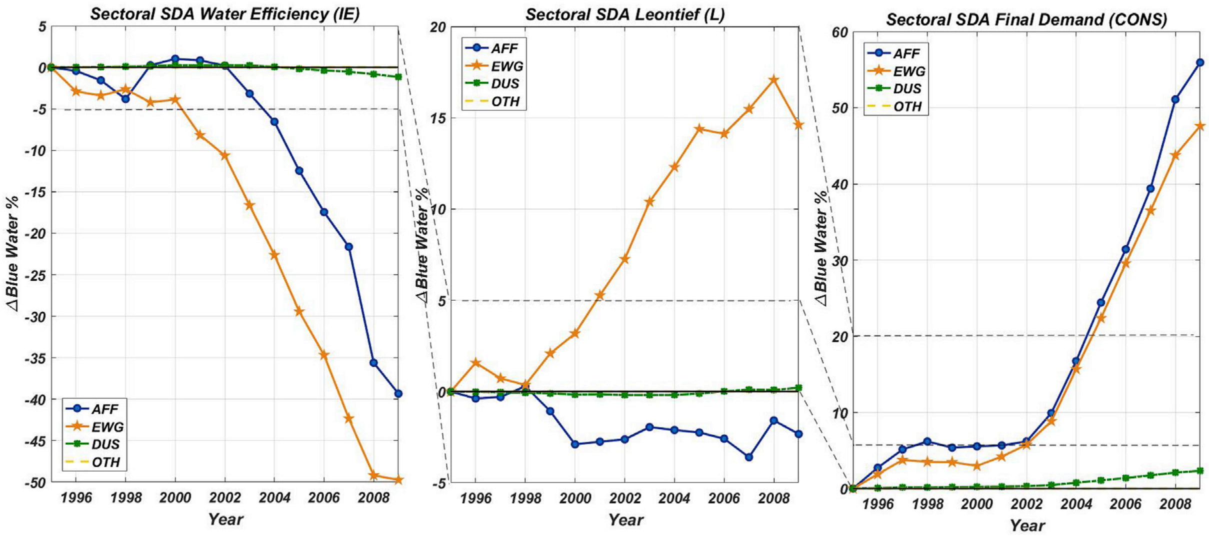

Fig. 7. Sectoral summary: time series (1995–2009) of the basic SDA for the four main macro-sectors: *AFF* (agriculture and food and beverage), *EWG* (energy and water transport), *DUS* (main industries that use water: chemical and paper), and the *OTH* (others). Left panel shows the change due to water effciency (IE), the central one the variation related to technology of production (Leontief), and on the right the impact of final demand (Cons). The percentages show the cumulative effect with respect to the water use in the base year (1995).

water is not available, due to some external reason (e.g. a drought), as a primary input of a production sector in a certain country. This shortage will impede the production of that sector that will not be able to export virtual water to other downstream sectors, giving rise to cascade effects. On the contrary, long-run changes in water availability cannot be evaluated with the kind of network statistics we discuss below as these long-run changes influence themselves the topology and structure of the virtual water input-output network.

Following [40], we compute the topology of the *BVWION*, that is described by the matrix Ω whose elements are the amount of direct virtual water (m^3)[21] exchanged for intermediate goods and services, defined as:

$$\Omega = \widehat{\gamma} \cdot Z \tag{7}$$

such that the row sum must be equal to the total amount of water used in each sector for the IO trade. Note that the vector γ is a filter, so that only those links for which the country-sector directly uses water have a positive weight in the whole IO network. It should be noted, however, that the network also include all the nodes (country-sector pairs) that do not use water directly but are connected (through inter-industry transactions) to country-sector pairs that do use water directly. This is particularly important when considering possible cascade effects.

We investigate the directed and weighted graph of the actual exchanges of (virtual) water embodied in each product.[22] In this way it is possible to complement the evidence arising from the SDA – which quantifies the role played by a variety of drivers of virtual water at the aggregate level – with useful information on the topology of the linkages among countries and sectors. Differently for many other existing studies that focus on the cross-country trade network [2,32,35], the main novelty in our paper is that we consider the country-sector pair as the node of the network. Links between nodes are directed on the basis of the flow of trade, from exporter to the importer, and they are weighted by the volume of *VW*.

Ω is the weighted adjacency matrix whose elements ω_{ij} represent the links between node *i* and *j*, that is the flow of *VW* that goes from *i* to *j*. Strictly-positive self loops $\omega_{ii} > 0$ capture the idea of an industry using its own products as inputs. Directed networks are typically asymmetric, meaning that $\omega_{ij} \neq \omega_{ji}$, so they allow to recover the information both from the importer and the exporter side. Let $k_{IN,i}$ be the *in*− node degree, that is the number of sectors that are exporting to sector *i*; while $S_{IN,i} = \Sigma_j \omega_{ij}$ is the *in*− node strength of node *i*, that is the total *VW* related to the amount of intermediate input purchased by sector *i*.[23] Symmetrically, we define the *out*− node degree $k_{OUT,i}$ and strength $S_{OUT,i}$ of node *i* as the sum of entries in row *i* of matrix Ω. These indicators provide information about the structure of *VW* network and of the presence of hubs (big importers or exporters), which influence the vulnerability of the whole system. The graph is composed by 1400 nodes (i.e., industries in different countries), each of which trades virtual water.[24] In what follows, we discuss a series of network statistics of interest for the whole graph Ω to assess its vulnerability to localized shocks at the level of single country-sector

[21] We filter the edges such that the minimum amount of virtual water traded is 1000 m^3. This simplifies the computation without affecting the results in a substantial way, since we preserve more than 99.99% of the total BVWION.

[22] Differently from the approach evaluated when considering VW trade, we here just consider direct requirements of water and not total requirements.

[23] This computation reminds the backward linkage index which returns the column sum of matrix *L* to assess the importance of a node.

[24] RoW has been removed because, by definition, it includes a great variety of countries, and then it does not represent a homogeneous entity. The topological structure is not affected by that, with the exception of the ranking, because RoW covers a big share of the virtual water globally traded.

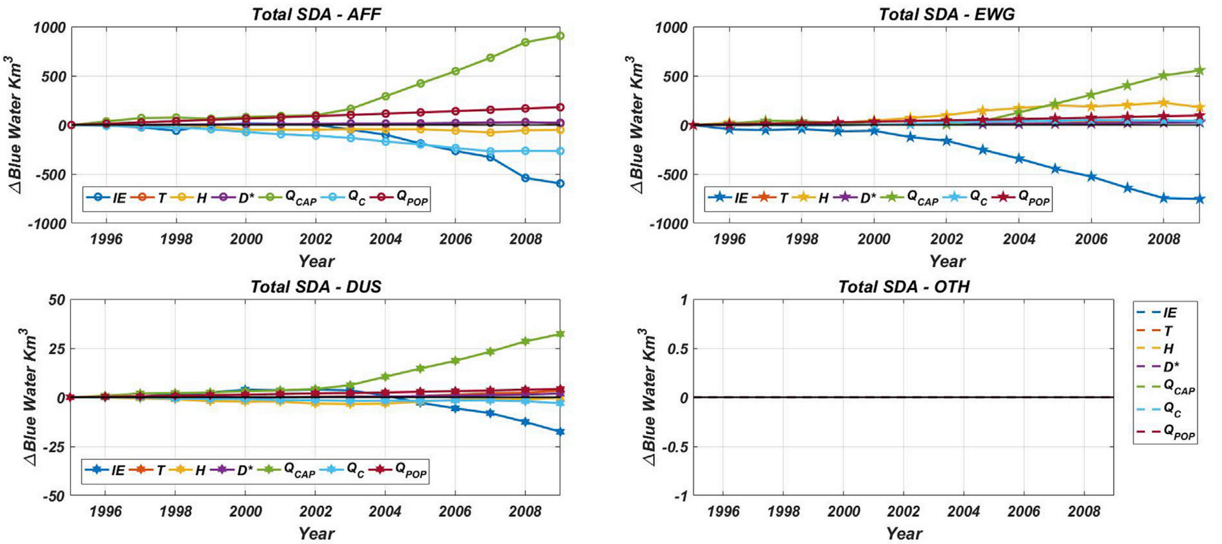

Fig. 8. Sectoral summary: time series (1995–2009) of the complete SDA – for all the seven variables listed in Section 4 – for the four main macro-sectors: *AFF* (top-left), *EWG* (top-right), *DUS* (bottom-left), and the *OTH* (bottom-right). The variations show the cumulative effect with respect to the water use in the base year (1995).

pairs. Moreover, to focus our attention on the international dimension of VW, we also provide a comparison of the total world VWN with the 'pure' international trade network (*IT*), that is obtained by excluding within-country trade from the matrix Ω, to check the scale-free behaviour of the network.

Although the number of edges (or links) is quite large ($\sim 10^5$), the share of active linkages with respect to all possible combinations (1400^2) is very low, although increasing over time from ~5% to about ~6%. This is not surprising because many sectors are characterized by a null direct water intensity coefficient.[25] In the case of the international trade network (IT), similar considerations hold true, although active linkages represent only ~4% of Ω. The distribution of node strength is highly variable both in space and over time. As expected, the maximum node out–strength (S_{OUT}), that is the magnitude of export links, is always greater than the maximum node in–strength (S_{IN}), that is the magnitude of import links. This happens because few industries are providing virtual water to all the others. In 1995 the highest out–strength values was ~90 Km^3 (~7 Km^3, in case of *IT*) and of ~143 Km^3 (~8.2 Km^3, in case of *IT*) in 2009. Similarly, for in–strength that oscillated from ~43 Km^3 (~2.2 Km^3, in case of *IT*) to ~52 Km^3 (~2 Km^3, in case of *IT*). This evidence suggests that the *BVWION* is expected to be characterized by scale-free behaviours by the presence of fat-tails. As discussed later in this section, these characteristics imply that the *BVWION* is particularly vulnerable to shocks due to cascade effects. Note that the basic statistics concerning the structure of the exchanges are really stable over time and are independent on the scale of analysis (not statistically significant differences are found over time, nor between the whole *IO* network and *IT*). The *IT* network appears to be even more stable over time than Ω.

Fig. 9 shows the time series of the share of *BVW* used by the top suppliers (out–strength) and buyers (in–strength). As expected the main sectors are *EWG* and *AtB*, with the interesting role played by *Fb* which is among the main absorbing sector in the *BVWION* of *IT*. The main countries identified in the previous Section are present here (Brazil, China, India, the US, and Japan) with mixed roles, sometimes as exporter and sometimes as importers, depending on the sector. Based on matrix Ω, we observe that virtual water use is concentrated in few pairs: in 2009 (1995) top 5 suppliers used together ~60% (~51%), while the buyers were sparser, the top 5 covered jointly only ~27% (~24%). In case of *IT*, the percentages are slightly higher and more stable: the cumulative percentage of the top 5 suppliers was ~65% over the whole time span, while the cumulative percentage of the top 5 suppliers was ~25%.

These results open the door to a deeper understanding of the asymmetric information coming from the importer (in–) and exporter (out–) side and on how the topology can inform us about the probability of propagation of micro–shocks through cascade-effects, that is the possibility to observe macro-fluctuations (global) due to local (supply–side) shocks.

5.1. Systemic vulnerability on the BVWION

Systemic risk is the risk that a local shock will affect several players (i.e., country–sector pairs) because it spreads to the entire economy through the interconnections among nodes. The structure of the network is a key component that can either attenuate or amplify systemic risk and thus its understanding is crucial to assessing, monitoring, and regulating VW systems. Most of the literature

[25] This is a specific feature of the data collected in WIOD, with the bulk of direct water usage concentrated in a reduced number of water-intensive sectors. If also direct water use of much less water-intensive sectors was considered, the number of active links would have been greater, even though these additional links would have been characterized by a very small average 'weight'.

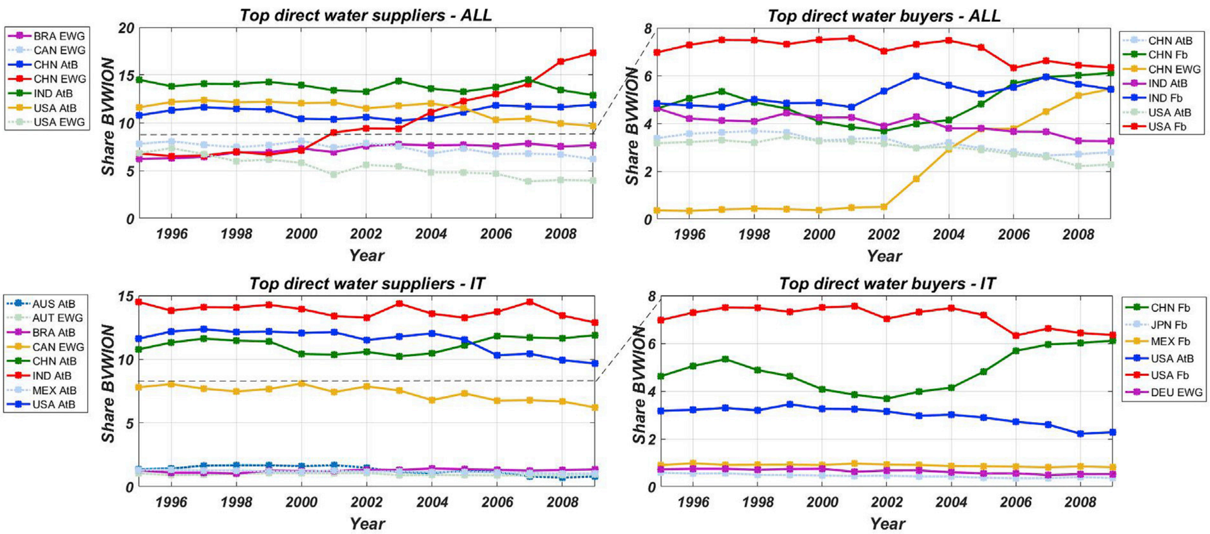

Fig. 9. Time series – from 1995 to 2009 – of the node strength for the top suppliers (left) and buyers (right), for both Ω (top) and international trade (bottom). Each country-sector pair represents a node. The sectors are: Agriculture, Hunting, Forestry and Fishing (*AtB*), Food, Beverages and Tobacco (*Fb*), and Electricity, Gas and Water Supply (*EWG*).

focused on the propagation of financial crises [27,37,39,40], while only few attempts have been made in the context of global food chains [4,38] and global VWN [52]. The concept of *vulnerability* refers to the possibility that idiosyncratic (micro–level) shocks propagate, due to the inter–sectoral linkages, leading to aggregate fluctuations. In particular, the rate at which aggregate volatility decays explicitly depends on the structure of the inter-sectoral network [40]. This explains why we only focus on matrix Ω and why we develop several indexes to evaluate the structure of the network and the distribution of (different kind of) connectivity degrees. In particular, substantial heterogeneity in the size and the interconnection among nodes, high levels of variability in the degrees of different sectors, and the presence of high degree sectors that share common suppliers, imply that the effects of a shock will dissipate at a lower rate and then that the shock can generate macro-level fluctuations.

The remarkable difference between *VWT* in final and intermediate goods deserves attention since most of the literature, so far, has been focusing on aggregate trade neglecting the impact of the unfolding of global production chains on water exchange and consumption. To the best of our knowledge, this is the first attempt to analyse the IO supply-chain in terms of *VW* vulnerability. Our results might represent an integration of previous literature that focused on final consumption and can enrich the framework of investigation toward wiser water management policies.

The analysis of the empirical distribution of *in*− and *out*− node degree and strength has been widely applied to assess the heterogeneity of the network connectivity and then the potential vulnerability [37,40]. A very common feature of many complex network is the so called "fat-tail" distribution, which means that extreme events (i.e., the upper and lower parts of the distribution) are more frequent than what expected in a Gaussian distribution. This fact has relevant repercussions on the stability of the trade relations and on the probability of local-shock propagation in the short term. Fig. 10 (top panels) shows the empirical probability density distribution[26] for both the *in*– (left) and *out*– (right) strength degree, with the distinction between Ω and IT. Given the stability of the structure over time, we draw the empirical probability density function from all nodes, of all years, pooled together. From the figure, nodes appear to be log-normally distributed, especially so in the case of IT. The most widespread fat–tail distributions analysed in the context of complex systems are the Log–Normal and the Power–Law ones. These two distributions appear very similar from an empirical viewpoint and often the distinction among the two is rather difficult [53,54]. Since here we are not interested in the statical process of generation of distribution, we compute both the main parameters of the Log–Normal distribution (mean and standard deviation) and we run (year specific) OLS regressions between the logarithm of node's degree and the logarithm of strength both for suppliers and buyers (Power–Law).

Table 2 reports the outcomes for each year of the Log–Normal parameters and the OLS estimations. The mean of the Log–Normal is really similar for buyers and suppliers, of about 10 (while in case of IT is ~ 7.5). The volatility (σ) is very similar in both cases (~ 3), slightly lower for importers. Interestingly, even the IT shows similar σ, meaning that the IT system is more volatile given that the mean is lower then in case of Ω.

The Power–Law relationship has the functional form: $S_{IN} \sim k_{IN}^{\xi}$ and $S_{OUT} \sim k_{OUT}^{\zeta}$ for buyers and suppliers, respectively. The coefficients were relatively stable over time: ξ was approximately 2.4 (2.2 for IT), while ζ was of approximately 2 (1.7 for IT), thus revealing a highly skewed relationship. These high values indicate that there is a strong (more than proportional) relationship between

[26] We apply the Kernel density smoothing function provided in Matlab statistical toolbox. See https://it.mathworks.com/help/stats/kernel-distribution.html for a detailed description.

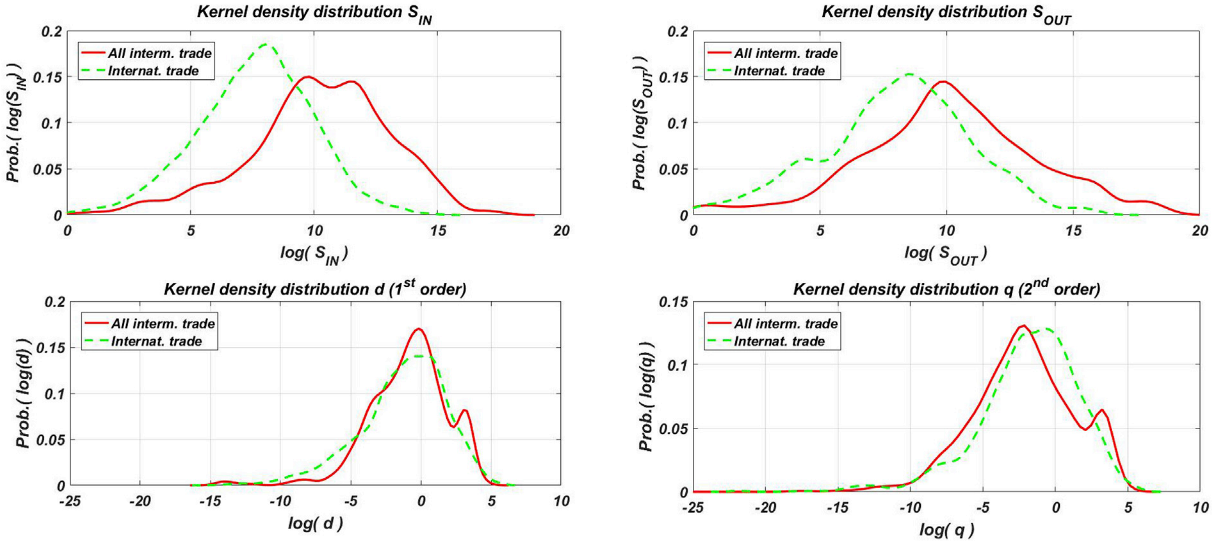

Fig. 10. Kernel Density distribution – data from all years pooled together – for: in-strength (top-left), out-strength (top-right), first-order connectivity degree (bottom-left), and second-order connectivity degree (bottom-right). All values are expressed in natural logarithm. Red lines stand for all intermediate exchanges (including domestic ones, matrix Ω), while the dash green lines stand for international trade only. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Fundamental parameters – mean (μ) and standard deviation (σ) – of the Log–Normal (*LogN*) distribution for both in-strength (S_{IN}) and out-strength (S_{OUT}). Results from the OLS – where SE means standard error and $R^2_{adj.}$ is the adjusted coefficient of determination – are computed on the logarithm of both degree (k) and strength (S) for both importers (*in*−) and exporters (*out*−). The coefficients ξ and ζ are estimated from the Pareto–Law function for the buyers and suppliers, respectively. The top panel of the table shows the outcomes for all the intermediate trade, while the bottom panel for the international trade only.

All Trade Ω	$LogN \sim S_{IN}$		$LogN \sim S_{OUT}$		Fit k_{IN} vs S_{IN}			Fit k_{OUT} vs S_{OUT}		
	μ	σ	μ	σ	ξ	SE	$R^2_{adj.}$	ζ	SE	$R^2_{adj.}$
1995	10.18	2.84	9.99	3.44	2.39	0.06	56.73%	1.99	0.08	67.45%
1996	10.18	2.89	9.99	3.46	2.43	0.06	58.32%	1.98	0.08	66.81%
1997	10.19	2.90	10.02	3.46	2.42	0.06	58.05%	1.99	0.08	66.88%
1998	10.26	2.85	10.01	3.49	2.39	0.06	56.06%	1.98	0.08	67.08%
1999	10.25	2.83	9.98	3.53	2.43	0.06	57.07%	1.96	0.08	68.00%
2000	10.26	2.87	10.07	3.46	2.40	0.05	59.14%	2.01	0.08	66.85%
2001	10.23	2.90	10.09	3.44	2.43	0.06	58.91%	2.00	0.08	66.44%
2002	10.19	2.86	10.10	3.42	2.43	0.06	57.64%	1.98	0.08	66.05%
2003	10.15	2.90	10.08	3.46	2.38	0.06	56.43%	2.00	0.08	68.94%
2004	10.25	2.88	10.12	3.50	2.40	0.06	56.28%	1.99	0.08	69.13%
2005	10.26	2.86	10.16	3.44	2.41	0.06	55.22%	2.00	0.08	67.72%
2006	10.29	2.87	10.24	3.41	2.47	0.06	56.21%	1.99	0.08	66.67%
2007	10.28	2.83	10.21	3.47	2.41	0.06	54.66%	1.99	0.08	68.19%
2008	10.30	2.83	10.18	3.51	2.40	0.06	54.19%	1.98	0.07	69.34%
2009	10.29	2.82	10.17	3.48	2.38	0.06	54.34%	1.99	0.08	68.70%
Intern. Trade	μ	σ	μ	σ	slope	SE	$R^2_{adj.}$	slope	SE	$R^2_{adj.}$
1995	7.29	2.39	7.79	2.90	2.15	0.03	81.05%	1.74	0.04	87.29%
1996	7.35	2.39	7.80	2.90	2.17	0.03	80.08%	1.73	0.04	86.88%
1997	7.44	2.42	7.95	2.88	2.21	0.03	80.06%	1.76	0.04	86.08%
1998	7.47	2.38	8.00	2.84	2.21	0.03	79.90%	1.79	0.04	86.20%
1999	7.55	2.34	7.96	2.90	2.20	0.03	79.49%	1.76	0.04	86.03%
2000	7.61	2.40	7.98	2.97	2.16	0.03	78.47%	1.76	0.04	87.09%
2001	7.65	2.36	7.97	2.98	2.16	0.03	77.13%	1.77	0.04	87.32%
2002	7.61	2.33	7.98	2.96	2.14	0.03	78.18%	1.76	0.04	87.12%
2003	7.62	2.33	8.00	2.97	2.12	0.03	78.16%	1.78	0.04	87.49%
2004	7.70	2.29	8.12	2.95	2.17	0.03	77.26%	1.79	0.04	86.74%
2005	7.72	2.30	8.17	2.90	2.15	0.03	77.08%	1.78	0.04	85.99%
2006	7.81	2.28	8.26	2.91	2.19	0.03	77.29%	1.79	0.04	85.68%
2007	7.87	2.24	8.21	2.95	2.12	0.03	75.90%	1.77	0.04	86.40%
2008	7.85	2.25	8.25	2.93	2.12	0.03	74.98%	1.77	0.04	85.87%
2009	7.79	2.23	8.16	2.94	2.12	0.03	75.75%	1.74	0.04	85.45%

the volume of virtual water that each country trades and the number of commercial partners. In other words, the *in*− /*out*− weighted degree (i.e. strength) grows faster than simple *in*− /*out*− degree, so the more trade connections a country has, the more it is able to participate in the exchange of VW in a highly non-proportional way. However, the rate of decay is far slower (for an estimated coefficient ξ, then the rate of decay is calculated as $n^{\frac{\xi-2}{\xi-1}}$ [55], pag.30], in our case it is about $n^{0.16}$) than in a Gaussian distribution (where the exponent is 0.5), meaning that shocks to sectors that take more central positions in the inter-sectoral network have a more than proportional effect on the whole system. In other words, we detect an increasing interdependency among rigid cross–country systems of water distribution and consumption that enables the extensive diffusion of risks. These results are robust over time. The adjusted R squared (R^2_{adj}), that provides an estimate of the share of total variance that is explained by the econometric model, reveals that the Power–Law is a good approximation for both *in*– and *out*– relations, and both in case of *BVWION* and *IT*. The smallest values are found in case of in– degree where the goodness of fit was ~ 55% (~ 75%, in case of *IT*), while the out– degree performed really well with R^2_{adj} of ~ 75% (~ 85%, in case of *IT*). These results are in line with the findings of [2], despite the fact that our study accounts for self-loops and that it focuses on inter-sectoral trade only (Ω).[27] In what follows, we introduce additional measures to understand whether benefits coming from higher trade connectivity (i.e. efficient redistribution of *VW* as explained in Section 3.1) are counterbalanced by greater systemic risks.

To provide a complete framework for the investigation of the systemic vulnerability of the network, we compute the first and second order network characteristics. The first–order connectivity degree (d) is an average of the importance of a sector as a direct supplier to its importers. The second–order degree (q) captures the indirect connections, that is the extent to which sectors with high degrees (those that are important suppliers to other sectors) are interconnected to one another through common suppliers. In other words, q_i is defined as the weighted sum of d_i of the sectors that use sector i's product as inputs, with weights given by the corresponding input shares.

The distinction between the two is crucial because two networks with identical *first*− *order* degree distributions might exhibit considerably different levels of vulnerability, because of the so called "cascade" effects [40]. Indeed, a country/sector-specific idiosyncratic shock affects not only those nodes immediately connected to it, but also those indirectly connected. First-order (d) and second-order (q) degrees are defined as follows:

$$\Psi = \Omega\cdot\left(\widehat{S}_{in}\right)^{-1} \tag{8}$$

$$d = \Psi\cdot\mathbf{i} \tag{9}$$

$$q = \Psi\cdot\widehat{d}\cdot\mathbf{i} \tag{10}$$

where Ψ is the matrix of weights, such that $\mathbf{i}'\cdot\Psi = \mathbf{i}$, where $\mathbf{i}$ is the summation vector.

Fig. 10 (bottom panels) shows the distribution of both d and q which are characterized by fat-tail behaviour. These findings suggest that the *BVWION* is vulnerable to idiosyncratic shocks due to indirect connections between sectors and countries. It means that the indirect inter-sectoral links potentially propagate the impact of a shock that hits a node (most notably if it is a 'big' exporter). Because of the scale-free behaviour the same considerations hold in case of *IT*. International input trade transmits shocks across borders in the same way as domestic input trade transmits shocks across sectors, they are passed downstream through the production chain directly in other countries and may generate remarkable variations in the amount of *VW* traded. Thus, the IT network input flows, despite their tiny fraction, might be a risky channel of water redistribution. The main implication is that remarkable aggregate fluctuations may originate from microeconomic shocks because the *BVWION* shows asymmetries in the roles that sectors play as direct or indirect suppliers to others.

Finally, Table 3 shows some descriptive statistics to check the presence of fat-tails in the distribution of first- and second-order connectivity degrees. Both skewness and kurtosis were positive and high, indicating asymmetric distributions and, compared to the normal distribution, a higher concentration around the mean and fatter tails. These values were always higher in case of IT and for the d index: this confirms that the international VWT could be a potential channel of shock diffusion mostly through indirect links (i.e. cascade effects) that indeed are captured by the second–order connectivity degree. Moreover, contrary to the findings of [38], we find that over time the kurtosis and skewness are increasing, together with the increasing standard deviation, confirming once again that the distributions become less balanced, and the possible presence of heavy tails increases the level of vulnerability due to local crises and abnormal events. This divergence in results confirms that including more sectors, than simply the agricultural one, might unravel new potential risks in the international VWT.

The extreme heterogeneity of the connectivity patterns, together with the large degree variability observed, are further signals of the presence of a scale-free distribution. Recent literature shows that the heavy-tailed nature of the degree distribution has also important consequences on the network *vulnerability* in case of removals of vertices or exogenous shocks to vertices [55]. A relevant parameter for these phenomena is the ratio between the first and the second moment of the distribution (i.e., the coefficient of variation, defined as λ). In case of directed networks, as those analysed so far, this heterogeneity parameter has to be defined separately for *in*− degrees ($\lambda_{S_{in}}$) and *out*− degrees ($\lambda_{S_{out}}$).

If $\lambda_{S_{in}} > 1$ and $\lambda_{S_{out}} > 1$ then the network manifests some properties that are not observed for networks with exponentially decaying

[27] Note that the scale-free behaviour allows to conjecture similar findings even when more data and details for the RoW will be available. Indeed, the system is stable at different levels of aggregation and the absence of the half of the *VW* trade (represented by the RoW) does not affect the topology.

Table 3
Statistical tests of fat-tail behaviour. Following [26], we compute some descriptive statistics: kurtosis, skewness, and standard deviation, for both the **d** (left) and **q** degree distributions (right). These values are positive and far greater than what expected in case of Gaussian distribution, confirming the fat-tail behaviour of both **d** and **q**. Moreover the Lilliefors test always rejects the hypothesis of normal distribution.

Year	First Order Degree (d)						Second Order Degree (q)					
	All Trade (Ω)			Intern. Trade			All Trade (Ω)			Intern. Trade		
	Kurtosis	Skewness	St. Dev	Kurtosis	Skewness	St. Dev	Kurtosis	Skewness	St. Dev	Kurtosis	Skewness	St. Dev
1995	15.4	3.2	9.8	19.6	3.7	11.6	62.4	6.8	14.8	82.1	7.8	16.6
1996	17.9	3.4	10.0	22.6	3.9	11.8	81.2	7.7	15.2	88.7	8.1	16.6
1997	16.0	3.3	9.8	20.5	3.7	11.7	77.2	7.6	15.1	93.9	8.5	17.6
1998	17.3	3.4	9.9	22.5	3.9	11.8	89.7	8.2	15.5	90.1	8.4	18.0
1999	19.9	3.6	10.0	25.5	4.2	12.1	86.3	8.0	16.1	75.8	7.8	17.5
2000	33.3	4.5	10.4	43.9	5.3	12.6	138.7	10.4	17.9	102.3	9.1	19.1
2001	30.8	4.4	10.4	43.2	5.2	12.5	139.6	10.5	17.8	130.6	10.3	21.2
2002	21.7	3.8	9.9	28.4	4.3	11.9	85.9	8.1	15.5	91.8	8.7	19.0
2003	21.7	3.7	9.8	29.0	4.4	11.8	90.0	8.3	15.3	97.2	8.9	18.4
2004	22.4	3.7	9.8	31.4	4.5	11.8	112.0	9.1	15.3	94.0	8.7	17.7
2005	27.7	4.1	10.0	41.4	5.1	12.3	120.2	9.5	16.1	93.8	8.6	17.3
2006	26.7	4.0	9.9	41.6	5.1	12.2	122.2	9.6	15.5	100.8	9.1	18.2
2007	44.4	5.2	10.4	65.2	6.4	13.0	147.7	10.7	17.0	103.9	9.3	19.0
2008	27.8	4.2	10.1	41.9	5.1	12.4	101.3	8.6	15.3	95.3	8.9	18.5
2009	46.6	5.3	10.8	67.3	6.6	13.3	148.1	10.8	17.2	94.4	8.9	18.7

degree distributions. Table 4 confirms the heavy-tailed behaviour when comparing the heterogeneity parameters and their high variances, with the only exception of the *in*–strength of IT. It should be noted, however, that in our context in which climatic shocks may influence the existence of nodes as suppliers of Virtual Water, what matters the most for the propagation of shocks are *out*–degrees. Because most of the analysed degree distributions are heavy-tailed, heterogeneity is very large so that the linear correlation coefficient between variables is not well defined for those cases. A full account of the connectivity pattern and of the system vulnerability requires

Table 4
Fundamental indicators of vulnerability to shocks of the *BVWION*, where: k stands for degree, S for strength (in Km^3), λ refers to the coefficient of variation, the degree correlations are found in eq. (11), and the assortativity refers to eq. (13) where "weightK" means assortativity coefficient weighted by total degree and "weightS" weighted by total strength. The top panel of the table shows the outcomes for all the intermediate trade, while the bottom panel for the international trade only.

All Trade Ω	Average		λ				Degree Correl.		Assortativity		
	k	S	k_{IN}	k_{OUT}	S_{IN}	S_{OUT}	$k_{in.out}$	$S_{in.out}$	*unweigthed*	*weightK*	*weightS*
1995	74.19	8.12	111	2662	11	203	1.6	23.3	−0.47	−0.023	0.044
1996	74.98	8.20	110	2719	12	210	1.6	22.9	−0.48	−0.023	0.043
1997	78.44	8.60	114	2772	13	219	1.6	23.6	−0.48	−0.022	0.042
1998	79.28	8.52	116	2767	12	214	1.6	23.8	−0.48	−0.021	0.043
1999	79.47	9.09	116	2781	12	216	1.6	24.8	−0.48	−0.020	0.043
2000	81.57	8.62	118	2807	12	213	1.6	23.0	−0.48	−0.021	0.042
2001	81.39	8.52	117	2840	12	209	1.6	23.2	−0.48	−0.023	0.042
2002	82.51	7.75	118	2866	11	211	1.6	22.4	−0.48	−0.022	0.044
2003	83.34	8.49	119	2869	13	223	1.6	24.4	−0.48	−0.020	0.044
2004	85.64	9.09	121	2918	14	241	1.5	25.6	−0.48	−0.020	0.043
2005	86.31	9.55	121	2936	14	258	1.5	26.7	−0.48	−0.020	0.042
2006	89.06	9.79	124	2997	15	274	1.5	26.4	−0.49	−0.019	0.042
2007	89.83	10.81	124	2997	17	298	1.5	28.4	−0.49	−0.019	0.039
2008	90.78	11.39	125	3000	17	315	1.5	29.6	−0.49	−0.020	0.038
2009	87.29	11.70	121	2969	18	322	1.5	31.1	−0.49	−0.021	0.038
Intern. Trade	k	S	k_{IN}	k_{OUT}	S_{IN}	S_{OUT}	$k_{in.out}$	$S_{in.out}$	*unweigth*	*weightK*	*weightH*
1995	67.59	0.08	106	2698	0.6	14	1.7	12.7	−0.50	−0.012	0.038
1996	68.49	0.08	105	2768	0.6	15	1.7	11.8	−0.51	−0.011	0.040
1997	71.95	0.11	109	2807	0.8	17	1.6	11.2	−0.51	−0.011	0.038
1998	72.79	0.10	110	2819	0.7	14	1.6	11.1	−0.51	−0.014	0.038
1999	72.90	0.11	110	2835	0.7	14	1.6	9.9	−0.51	−0.016	0.036
2000	75.05	0.11	113	2820	0.7	18	1.6	8.3	−0.51	−0.017	0.037
2001	74.99	0.10	112	2846	0.6	16	1.6	8.3	−0.51	−0.020	0.039
2002	75.96	0.09	112	2873	0.5	11	1.6	9.4	−0.51	−0.020	0.046
2003	76.81	0.08	113	2874	0.5	11	1.6	10.0	−0.51	−0.019	0.045
2004	79.27	0.11	116	2932	0.5	13	1.6	9.2	−0.51	−0.016	0.045
2005	79.75	0.10	116	2960	0.5	13	1.6	8.6	−0.51	−0.021	0.044
2006	82.52	0.12	118	2999	0.5	13	1.5	8.6	−0.52	−0.020	0.045
2007	83.24	0.12	119	2988	0.6	15	1.5	9.2	−0.52	−0.019	0.043
2008	84.13	0.13	119	3010	0.7	19	1.5	9.7	−0.52	−0.014	0.041
2009	80.85	0.13	116	2992	0.6	17	1.5	9.2	−0.52	−0.017	0.040

further non-linear indicators of degree correlations. First, we compute the so called *one-point degree correlations* ($k_{in.out}$ and $S_{in.out}$) for individual nodes, in order to understand whether a relation exists between the number of incoming and outgoing links in single nodes. These one-point degree correlations are computed as:

$$k_{in.out} = \frac{< \Sigma_i k_{in,i} \cdot k_{out,i} >}{< k_{in} >^2} \tag{11}$$

$$S_{in.out} = \frac{< \Sigma_i S_{in,i} \cdot S_{out,i} >}{< S_{in} >^2} \tag{12}$$

A significant positive correlation between the in-degrees and the out-degrees of single nodes is found in each year, as summarized in Table 4. This implies that sectors that have a high number of input-demand relations, i.e. a high in-degree, also tend to supply their output to a relatively high number of other sectors. This information is crucial to better understand the structure of international trade shown in Fig. 1. To the best of our knowledge the assessment of these values for environmental variables is novel in the literature.

Finally, the assortativity index measures the similarity of connections in the graph with respect to the node strength, hence it is a correlation coefficient between the strengths (weighted degrees) of all nodes on two opposite ends of a link. This measure is a natural candidate to investigate the correlation of the degrees of neighboring vertices. Through this index, we assess whether relatively high degree nodes have a higher tendency to be connected to other high degree nodes. A positive assortativity coefficient indicates that nodes tend to link to other nodes with the same or similar strength. This property was defined by Ref. [56] for un-weighted networks, while here we introduce the weighted and directed version [57,58]:

$$r^{\omega} = \frac{\frac{\sum_j \sum_i S_j \cdot S_i}{2P} - \left(\frac{\sum_j \sum_i S_j \cdot S_j}{2P} \right)^2}{\frac{\left(\sum_j \sum_i S_j^2 \cdot S_i^2 \right)}{2P} - \left(\frac{\sum_j \sum_i S_j \cdot S_i}{2P} \right)^2} \tag{13}$$

where P is the sum of the weighted edges of the network – either total degree (column "weightK" in Table 4) or total strength (column "weightS" in Table 4) – and the double summation is computed only for positive links (i.e., $\omega_{ji} > 0$). We compute the assortativity index for each of the four possible combinations (out–out, in–in, in–out and out–in), finding very similar results (Table 4 reports an average value). The weighted values were close to zero, negative if weighted by degree and slighlty positive if weighted by strength.[28] Then, we do not identify a clear behaviour, suggesting that high degree (strength) country-sector pairs tend to have trade relationships both with small and big country-sector pairs. In other words, this result indicates that nodes that trade large volumes of water are highly connected with many other country-sector pairs, so that large volumes of water can be reallocated among several countries, representing a potential water security tool (confirming the finding of Section 3.1).

6. Learning from SDA and network analysis of VW

The above analysis, that combines structural decomposition analysis and network analysis, highlights a trade-off in the *BVWION*. The global network of virtual water might benefit from increasing exchanges. However, it might be a risky channel because it facilitates the propagation of shocks. The topological properties of the current *VW* network bring about some relevant implications that call for policy actions aimed at reducing and mitigating the propagation of shocks in the supply of water due to the increasing climatic risks. Actions should necessarily involve a coordinated set of measures across countries due to the high degree of dependence on foreign water resources for many countries.

Not only 'big' countries but also smaller ones should be included: Fig. 1 shows a positive relation between the endowment of *Wa* and the level of net import of *VW* (and thus of higher level of external 'dependency' and thus exposure to external shocks). Being part of the *VW* network increases a country's vulnerability to crises that occur in other countries involved in the network, due to the cascade effects. In other words, there is a potential trade-off between the need to import water-intensive goods (and the associated potential saving in water resources) and the vulnerability to external shocks. Moreover, from the inter-temporal comparison of the *first−* and *second−* order connectivity degrees and of the indexes of degree correlations it emerges an increasing tendency of the water network to be more vulnerable in time. These are remarkable results about the possibility to incur in imminent crises.

Finally, our results highlight the necessity to reinforce initiatives toward coordinated local and global water management strategies to reduce the risks coming from water stress. Therefore, understanding the structure of this network can inform policy-makers on how to prepare for and recover from adverse shocks that alter the provision and distribution of water.

7. Concluding remarks

In this paper we study the global network of virtual water exchanges by adopting a multi-faced approach that integrates Input Output Analysis and Network Analysis. This approach proved to be fruitful in providing a wide picture of the issues at stake, highlighting that

[28] This results is slightly in contrast with those of [2].

a trade–off may exist between an efficient allocation of water intensive production in water abundant countries to guarantee virtual water to water scarce countries and a VW trade network that prevents the propagation of risks. Our analysis contributes to the existing literature that analyzes the VW trade network (e.g. Refs. [38] and [35]) by considering all possible uses of blue water in many different sectors. The present work also contributes to the debate about the potential merits and risks associated with high trade connectivity for water security. SDA allowed to unravel the main drivers of *VW* and their evolution over time. There was a substantial contribution to reducing water demand exerted by the composition of final demand and by improvements in the water efficiency of production, while demographic and economic growth and changes in the intermediate input mix have more than compensated such reduction. Interestingly, the role played by changes in trade patterns was rather marginal, contributing only to a moderate increase in virtual water. Besides the aggregate picture, we also observe some peculiarities in specific countries that seem to be related to their level of affluence and their trajectory of structural change and economic growth. Overall, SDA analysis showed that the growing usage of water has been only marginally affected by the increase of virtual water trade.

Network theory captures the non-linear relationships between *in*− and *out*− node strength and degree distributions that follow a Power–Law distribution. This finding has important implications for the trade policy of water-scarce countries that look to increase their (virtual) water availability because the amount of *VW* increases more than proportionally with the number of commercial partners. This means that increasing the number of trade partners through bilateral or multilateral trade agreements would allow water-scarce countries to increase substantially their consumption of water-intensive commodities. The fat-tail behaviour of the *first*– and *second*–order connectivity measures confirms that the system is particularly exposed to the propagation of localized supply-side shocks due to 'cascade effects' [40]. The main policy implication of these two findings is that a cross-country coordination of water management policies is needed to reduce the vulnerability of the world water supply system to negative shocks that might hit some crucial nodes, that would otherwise propagate to a large number of nodes.

When looking at both SDA and network analysis it turns out that the component 'international trade' is still relatively small in relative terms. On the other hand, the technological components (H and γ) have ensured to save almost 30% of water at global level.[29] This finding points to a possible response to perturbations to the VW network, that is to improve water efficiency of production and consumption. This important feature has been captured by the combination of the two methodologies that, in isolation, cannot describe effectively both the systematic risks and the dynamic evolution of the *VWT*. The *duality* of trade is determined by the apparent minor role played by trade evidenced by the SDA coupled with the potential risks related to the propagation of shocks in water supply across sectors and countries, evidenced by network analysis. In other words, there is still large room for reducing the virtual water requirements by reallocating intermediate and final consumption towards more water-efficient countries. Such reallocation, however, would come at the cost of greater exposure to propagation of shocks in the supply of water from specific countries. This duality is particularly challenging for what concerns the negotiation of international trade agreements and of international agreements aimed at promoting water security and an efficient use of water. A reduction of trade barriers may help, in principle, to improve the allocation of production of water-intensive products in water-efficient (with lower use of water per unit of production) countries. This would come at the cost of increasing the vulnerability of the virtual water network.

Results from connectivity and centrality measures underline the presence of a the disassortative network meaning that countries that trade large volumes of water are 'open' to trade with many other countries, so that large volumes of water can be reallocated among several countries, representing a potential water security tool. Our results largely differ from some recent findings in the literature. In particular [38], found that the *VWT* network is more interconnected, but not necessarily less stable. The key difference between our approach and the one followed in Ref. [38] is that we look at the larger network of industry and country specific relationships, considering all products in the economy, whereas they study the aggregate cross-country network of exchanges of food commodities. Thus we find an extremely skewed connectivity distribution among country-industry pairs while the distribution is usually less concentrated when studies are carried on at the country level.

Our findings call for coordinated actions to better manage water scarcity through the development of transboundary agreements and policies both at global and regional level. Trade in commodities is an imperfect substitute for the mobility of factors. This problem is exacerbated in case of freshwater, that is locally extracted and cannot be cheaply transferred abroad. Our study aims at focusing the attention on an efficient (in terms of reducing the amount of resource per unit of production) and rational exploitation of a scarce resource, such as freshwater, that is sometimes overlooked in production decisions and in international agreements. The process of globalization should then be matched with a process of international cooperation because countries' actions are not confined to their territorial jurisdiction, but they might interfere, directly or indirectly, with the enjoyment of the right to (virtual) water in other countries. Currently, there is an imbalance between international trade agreements (under the WTO system) and international agreements on sustainable water use, being the former strong, detailed and enforceable, whereas the latter are weak, unsophisticated, and with low enforcement power. An extensions of WTO rules on trade in virtual water is needed with the aim of conserving domestic water resources in water-scarce countries by means, for example, of export bans on water intensive products on the basis of serious concerns over conservation of domestic water resources or tariffs that consider the amount of water that has been used to produce imported products. This approach may look similar to the one proposed to tackle the issue of carbon leakage in the context of climate change by

[29] It is important to recall that these two technological components consider two different dimensions of technological improvement: H identifies the contribution of changes in the mix of intermediate inputs to the demand for virtual water for a given mix of consumption and direct requirement of water per unitary output while γ considers reduced direct water requirements to produce a certain level of monetary output (for a given mix of production and consumption). Due to the rather high degree of sectoral aggregation, γ also account for within-sector changes in the mix of products, such as the move from water-intensive crops to more water-efficient crops within the agricultural sector.

means of so-called carbon tariffs. Similarly to carbon tariffs, a ‘water tariff’ may be difficult to implement within the WTO rules [59] and would require specific international negotiations.

Water is central in the debate about climate change, especially so for what concerns adaptation strategies. During the CoP21 in Paris (December 2015), a large number of parties identified the water sector as the first priority area for mitigation actions, followed by agriculture that is also strictly connected to the water sector. In the “Synthesis report on the aggregate effect of the intended nationally determined contributions” proposed by the participating parties before the CoP21 (30 October 2015)[30] we read that “*Water security is clearly a key development priority for most Parties and therefore various types of action related to the protection of water resources have been included in the adaptation components. These generally aim at saving water, ensuring security of supply, enhancing the allocation of water and broadening the resource base.*”

This means that a likely large share of the funds that parties agreed to mobilise for mitigation and adaptation (at least USD 100 billion by 2020) will be devoted to actions aimed at adapting the water sector to climate-related disruptions. A comprehensive consideration of virtual water trends, topology and evolution is of crucial importance for an efficient and effective allocation of these economic resources.

Appendix A. Structural Decomposition Analysis

IO allows to identify and quantify the main drivers of change through the so called *structural decomposition analysis (SDA)* which allows to disentangle technological change from shifts in the final demand (see Ref. [48], Ch. 13). Let x be the vector of total output, and t and $t+1$ be two consecutive periods (i.e., years) expressed in a common base-year price, then it is possible to decompose the variation as:

$$\Delta x = x_t - x_{t-1} = \frac{1}{2}[\Delta L\cdot(f_t + f_{t-1}) + \Delta f\cdot(L_t + L_{t-1})] \tag{A.1}$$

where the first term, on the right hand side, expresses the change of the IO structure (technology and trade) and the latter the effect of a variation of final demand. It has long been recognized, in the literature on SDA, that there is not a unique criteria to do a decomposition. The results may differ significantly across the alternative procedures (see Ref. [60] [22]; for comparisons). To overcome the non-uniqueness problem, it is possible to use the average of all possible decomposition forms [60]. In case of n determinants (or variables), the number of alternative decompositions is $n!$. The average of all decompositions can be adequately approximated by the average of the two so-called *polar decomposition* forms. The first polar form is derived by starting the decomposition with changing the first variable, followed by changing the second variable, changing the third variable, and so forth. The second polar form is derived exactly the other way around, i.e. changing the last variable first, followed by changing the second-last variable, and so on.

Here, we propose and additive decomposition [22] of equation (2) to describe the increase from year t - 1 to year t of the total water use:

$$\Delta w = w_t - w_{t-1} = \Theta_{IE} + \Theta_{TECH} + \Theta_{CONS} \tag{A.2}$$

where Θ_{IE} represents the *intensity effect* (i.e., water efficiency), that is the variation of water use for any unit of output (γ), computed as:

$$\Theta_{IE} = \frac{1}{2}[\Delta\widehat{\gamma}\cdot L_t\cdot f_t + \Delta\widehat{\gamma}\cdot L_{t-1}\cdot f_{t-1}] \tag{A.3}$$

Afterwards, we calculate Θ_{LEON} that captures the variation of Leontief coefficients, from which it is possible to recover the impact from the change in the technological composition (H) and in the trade structure (T) of intermediate goods exchanges. Static comparative analysis allows to quantify the variation in water requirements given a change of matrix L, by keeping all the other variables unchanged (i.e., *ceteris paribus* condition), as:

$$\Theta_{LEON} = \frac{1}{2}[\widehat{\gamma}_{t-1}\cdot\Delta L\cdot f_t + \widehat{\gamma}_t\cdot\Delta L\cdot f_{t-1}] \tag{A.4}$$

Finally, Θ_{CONS} represents the variation of virtual water due to a shift in the volume of final demand, both at domestic and international level:

$$\Theta_{CONS} = \frac{1}{2}[\widehat{\gamma}_{t-1}\cdot L_{t-1}\cdot\Delta f + \widehat{\gamma}_t\cdot L_t\cdot\Delta f] \tag{A.5}$$

The additive chaining technique allows to recover the whole variation, from the first and the last year of interest, simply by summing consecutive one-year decompositions:

$$\Delta w_{(T,0)} = w_T - w_0 = \sum_{\tau=1}^{T}\Delta w_{(\tau,\tau-1)} \tag{A.6}$$

Here, we further decompose Θ_{LEON}. We start by computing the matrix $H_{(35x1435)}$ which gives the sum of technical coefficients of A, for each sector, by including all the intermediate imports of each country. The component H should be interpreted as the contribution to

[30] The document is available at the following link: http://unfccc.int/resource/docs/2015/cop21/eng/07.pdf.

water of changes in the mix of intermediate inputs with no consideration of the geographical origin of intermediate inputs. For country C we have H_C of size 35×35:

$$H_C = \sum_{j=1}^{R} A_{j1} \tag{A.7}$$

Matrix $T_{(1435x1435)}$, whose elements are the ratios between regional technical coefficient with respect of total technical coefficient (H), captures the impact of different a different geographical compositions of intermediate goods. For country C we compute T_{jC} $\forall j\varepsilon R$, as:

$$T_{jC} = A_{jC} \odot H_C \tag{A.8}$$

where $\odot$ indicates the Hadamard product, which, in this case, is the element-wise ratio for two matrices of the same dimensions. Recall that matrix A includes both T and H, then we rewrite ΔL, with respect to H and T, through matrix A. In particular, we apply the multiplicative decomposition of the Leontief inverse:

$$\Delta L_{POLAR} = \frac{1}{2}\left[L_{t-1} \cdot \Delta A_{POLAR} \cdot L_t + L_t \cdot \Delta A_{POLAR} \cdot L_{t-1}\right] \tag{A.9}$$

hence:

$$\Delta A_{POLAR} = \frac{1}{2}\left[(\Delta T \circ H_t + \Delta T \circ H_{t-1}) + (T_t \circ \Delta H + T_{t-1} \circ \Delta H)\right] \tag{A.10}$$

where $\circ$ is the Hadamard product, which is the element-wise product for two matrices of the same dimensions.

At this point it is worth to decompose the matrix of final demand ΔF in order to find the trade structure and the impact of product mix distribution over time. We assess the impact of population of per capita consumption. Let define $\tilde{F}$ as a RSxR matrix where each column accounts the national distribution of final demand by considering both domestic consumption and imports, for each sector. Let q be the overall level of the final demand, then for country C we have:

$$q_C = \sum_{j=1}^{R} \tilde{F}_{jC} \tag{A.11}$$

which is a column vector with the distribution of domestic demand plus imports of country C over all the 35 sectors. Let $\tilde{D}$ be the trade structure for final products, then – for each country C – we compute $\tilde{D}_{1C}, \tilde{D}_{2C}, \ldots, \tilde{D}_{RC}$, or in general for each $j\varepsilon R$:

$$\tilde{D}_{jC} = \tilde{F}_{jC} \odot q_C \tag{A.12}$$

Afterwards, we decompose q by taking into account the population size. Let Q be the vector of total demand in each country and $\Phi = \sum_{c=1}^{N} q_C$ be the product of population and consumption per capita, that is also given by $\Phi = q_{POP} \cdot q_{CAP}$. Moreover, let $\tilde{q}$ be the relative distribution of total final demand by sector, i.e for country C we have that Φ_C is a scalar, then:

$$\tilde{q}_C = q_C / \Phi_C \tag{A.13}$$

The final demand vector $\tilde{F}_{kC}$ of country C, for any j = 1,2, …,R, is given by:

$$\tilde{F}_{kC} = \tilde{D}_{kC} \circ \left(\tilde{q}_C \cdot q_{CAP,C} \cdot q_{POP,C}\right) \tag{A.14}$$

Polar decomposition technique reduces the computation to only two equations, the first one in which the static comparative analysis starts from the first component (D), while the second equation beginning from the last element (POP). In this case the polar decomposition for the final demand is given by:

$$\Theta_{CONS} = D^* + Q_C + Q_{CAP} + Q_{POP} \tag{A.15}$$

where D^* is the polar decomposition of the final demand trade structure, which is the counterpart for final demand of the component T:

$$D^* = \frac{1}{2}\left[\Delta D \circ q_t + \Delta D \circ q_{t-1}\right] \tag{A.16}$$

Q_C represents the variation of in the distribution of the demand among sectors, it quantifies the role played by changes in the product mix of final demand for a given level of final demand and for a given ‘geographical’ composition of final demand:

$$Q_C = \frac{1}{2}\left[(D_{t-1} \circ (\Delta(\tilde{q}) \cdot Q_t) + (D_t \circ (\Delta(\tilde{q}) \cdot Q_{t-1})\right] \tag{A.17}$$

Finally, Q_{POP} and Q_{CAP} indicate the impact of population and consumption per capita growth, respectively:

$$Q_{CAP} = \frac{1}{2}\left[(D_{t-1}\circ(\tilde{q}_{t-1}\cdot\Delta q_{CAP}\cdot POP_t) + (D_t\circ(\widetilde{q}_t\cdot\Delta q_{CAP}\cdot POP_{t-1})\right] \tag{A.18}$$

$$Q_{POP} = \frac{1}{2}\left[(D_{t-1}\circ(\tilde{q}_{t-1}\cdot q_{CAP,t-1}\cdot\Delta POP) + (D_t\circ(\widetilde{q}_t\cdot q_{CAP,t}\cdot\Delta POP)\right] \tag{A.19}$$

Therefore, equation (2) can be rewritten as:

$$w = \widehat{\gamma}\cdot(I - T\circ H)^{-1}\cdot(D^{*}\circ(\tilde{q}\cdot q_{CAP}\cdot POP)) \tag{A.20}$$

where POP is the total population, and $\widehat{\gamma}$ is a diagonal matrix composed by the entries of the array γ.

Appendix B. Additional tables

Table B1

Time series (1995–2009) of the water intensity coefficients (γ), in terms of $m^3/\$$ – for the three main macro-sectors: *AFF*, *EWG*, *DUS*, and *OTH* – for a selection of developed (the USA, Canada, Japan, and Australia) and Developing countries (China, India, Brazil, and Russia).

ISO	Sector	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
AUS	*AFF*	435.4	417.6	513.8	610.7	590.1	559.4	599.0	612.5	370.8	322.3	368.2	425.3	247.6	196.8	237.0
	EWG	222.7	198.8	204.4	210.9	211.1	222.0	237.8	198.7	165.3	138.7	115.1	115.9	84.4	66.0	71.5
	DUS	5.3	5.0	5.2	6.1	6.0	6.6	7.2	6.5	5.2	4.3	4.1	4.1	3.6	3.4	3.3
	OTH	0.6	0.6	0.6	0.8	0.7	0.7	0.8	0.7	0.6	0.4	0.4	0.3	0.3	0.3	0.3
BRA	*AFF*	200.2	165.0	163.2	153.4	258.7	231.4	255.0	260.8	215.2	208.9	180.1	161.3	123.6	106.1	118.4
	EWG	1936.5	1815.7	1792.0	1672.8	2280.8	2042.1	2003.6	2229.1	2230.5	1881.7	1509.8	1306.7	1181.1	1005.0	1121.5
	DUS	8.6	8.6	8.6	9.0	12.2	10.6	12.4	13.7	11.8	10.4	8.6	7.3	6.2	5.3	5.6
	OTH	3.6	3.6	3.7	3.9	5.3	4.7	5.3	5.3	4.6	3.7	2.6	2.3	1.9	1.5	1.7
CAN	*AFF*	58.7	56.4	55.0	64.4	65.4	60.5	57.9	58.9	55.9	43.7	43.7	45.8	38.1	37.1	38.9
	EWG	3715.5	3836.1	3781.2	3836.6	3819.6	3595.1	3322.3	3577.8	2878.1	2694.5	2453.3	2268.6	2227.0	2114.3	2317.2
	DUS	33.3	34.6	36.5	38.7	38.6	36.0	37.2	38.4	34.2	31.3	29.3	28.0	27.4	26.3	30.3
	OTH	7.7	7.9	7.9	8.6	8.6	8.3	8.9	8.9	8.0	6.6	6.2	5.9	5.8	5.6	6.4
CHN	*AFF*	535.7	482.5	481.2	450.2	454.7	416.2	379.4	357.0	323.0	285.6	277.6	265.7	215.4	173.9	165.3
	EWG	1327.4	1183.3	956.6	893.9	767.8	795.7	878.0	803.8	606.9	465.6	392.9	424.7	335.9	313.9	312.8
	DUS	30.2	27.6	28.4	30.3	30.9	28.8	29.0	29.7	29.3	27.6	26.0	25.1	23.5	19.9	20.7
	OTH	9.5	9.6	9.8	10.3	10.7	10.6	10.8	11.2	10.7	9.5	8.8	8.2	7.2	6.0	6.8
IND	*AFF*	1867.6	1786.0	1746.3	1729.5	1777.5	1835.2	1755.2	1734.2	1540.5	1452.3	1282.2	1248.9	1119.4	1067.2	1008.7
	EWG	683.8	663.3	630.4	647.8	671.2	615.5	612.7	471.8	504.2	523.3	557.1	564.0	499.8	474.6	401.9
	DUS	45.3	49.1	50.7	55.3	52.2	50.0	50.6	51.4	48.9	46.8	44.4	43.1	38.1	37.9	43.6
	OTH	11.3	11.8	11.7	13.0	13.4	13.4	14.1	14.0	11.5	9.2	8.3	8.0	6.8	6.2	6.8
JPN	*AFF*	16.0	18.1	19.9	19.6	17.9	18.1	20.4	20.9	17.8	18.1	19.5	20.0	20.6	17.6	16.5
	EWG	79.7	89.3	107.4	120.5	98.4	93.6	100.8	104.4	113.5	104.5	85.7	102.3	85.5	74.3	70.0
	DUS	2.6	3.0	3.3	3.6	3.2	3.0	3.4	3.6	3.3	3.0	3.0	3.1	3.1	2.6	2.6
	OTH	0.4	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.5	0.4	0.5	0.4	0.3	0.3
RUS	*AFF*	235.4	183.3	238.3	194.9	354.8	372.4	323.6	330.3	266.7	253.4	226.3	203.3	162.7	166.6	169.7
	EWG	1287.7	749.4	697.5	946.8	2517.0	2081.1	1713.9	1316.5	986.0	846.9	689.1	527.8	422.7	325.0	385.4
	DUS	132.2	98.7	90.8	126.8	252.5	224.9	198.3	194.2	178.1	129.9	110.7	96.8	77.9	63.1	76.6
	OTH	5.2	4.7	4.5	5.3	7.6	6.9	6.5	6.5	5.2	3.7	3.2	2.6	2.1	1.7	2.5
USA	*AFF*	374.7	371.3	380.6	387.8	404.8	411.1	398.0	391.4	369.2	361.1	359.4	337.9	307.0	270.5	310.7
	EWG	322.4	345.3	321.3	284.9	225.5	172.8	107.1	205.7	207.9	200.1	171.5	186.1	151.4	138.7	174.1
	DUS	24.0	23.9	23.7	23.0	22.8	22.3	22.2	22.2	21.9	21.2	20.0	19.0	18.6	17.6	17.5
	OTH	7.7	7.8	7.7	7.7	7.9	7.7	7.8	7.8	7.7	6.9	6.4	5.8	5.6	5.1	5.6

Table B2

World summary: time series (1995–2009) of the net *BVWT* balance (export - import) for all countries. The values are expressed in Km^3.

ISO	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOT
AUS	2.89	3.28	4.64	3.88	4.21	4.53	4.94	4.16	0.86	0.02	−0.18	−0.01	−2.55	−2.52	−2.23	25.95
AUT	−0.03	−0.15	0.28	0.31	0.47	0.43	0.21	1.29	0.79	0.57	0.68	0.68	0.98	1.05	1.07	8.62
BEL	−2.88	−2.96	−2.95	−3.02	−3.28	−4.03	−4.13	−4.01	−4.53	−4.97	−5.82	−5.65	−5.17	−5.17	−5.30	−63.87
BGR	0.16	0.28	0.36	0.26	0.15	0.16	0.09	0.15	0.22	0.18	0.23	0.29	0.05	−0.06	0.05	2.57
BRA	1.55	0.61	1.03	1.00	4.34	4.13	5.65	9.02	10.12	12.55	11.37	10.47	9.36	7.97	8.35	97.49
CAN	18.80	20.39	19.93	19.71	20.27	24.43	21.88	19.26	17.00	14.91	18.08	15.57	15.88	15.72	12.82	274.65
CHN	20.87	18.02	19.77	17.99	15.54	15.11	15.67	17.64	19.94	26.17	36.13	45.03	48.89	49.29	38.91	404.98
CYP	0.00	−0.05	−0.07	−0.04	−0.10	−0.10	−0.12	−0.10	−0.11	−0.11	−0.15	−0.13	−0.14	−0.25	−0.15	−1.63
CZE	−0.74	−0.86	−0.85	−0.83	−0.88	−0.97	−1.06	−1.04	−1.12	−1.20	−1.24	−1.27	−1.39	−1.52	−1.26	−16.21
DEU	−19.42	−17.45	−16.22	−17.38	−18.29	−19.78	−19.43	−18.45	−20.30	−21.16	−21.34	−22.15	−23.15	−22.81	−21.71	−299.05
DNK	−1.47	−1.36	−1.32	−1.31	−1.30	−1.30	−1.36	−1.44	−1.41	−1.62	−1.73	−1.75	−1.82	−1.80	−1.45	−22.46

(continued on next page)

Table B2 (*continued*)

ISO	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOT
ESP	−2.78	−0.68	0.78	−0.19	−1.78	−0.92	−0.68	−1.76	−1.15	−2.99	−4.99	−4.29	−4.97	−4.76	−2.18	−33.34
EST	−0.08	−0.10	−0.13	−0.16	−0.16	−0.18	−0.19	−0.22	−0.25	−0.25	−0.23	−0.27	−0.28	−0.26	−0.18	−2.94
FIN	−0.24	−0.29	−0.22	−0.27	−0.62	−0.17	−0.50	−0.46	−0.67	−0.35	−0.80	−0.80	−0.69	−0.52	−0.73	−7.34
FRA	−6.33	−6.17	−4.92	−6.33	−5.97	−6.48	−6.67	−7.12	−8.57	−9.25	−9.63	−9.52	−10.13	−9.84	−9.00	−115.93
GBR	−10.68	−11.29	−11.48	−12.68	−13.87	−14.31	−14.07	−14.01	−14.25	−17.89	−18.96	−19.71	−19.92	−17.79	−14.85	−225.75
GRC	−0.61	−0.72	−0.71	−0.79	−0.72	−1.07	−1.17	−1.40	−1.46	−1.59	−1.49	−1.63	−1.93	−2.13	−1.69	−19.09
HUN	−0.54	−0.54	−0.49	−0.60	−0.79	−0.88	−0.89	−0.92	−0.98	−0.91	−0.97	−0.92	−0.99	−0.94	−0.75	−12.11
IDN	−0.66	−1.05	−1.48	1.02	−0.28	−0.44	−0.88	−1.56	−1.39	−1.53	−1.12	−1.91	−2.13	−2.02	−2.07	−17.51
IND	17.09	16.81	19.29	18.70	21.41	22.95	20.64	20.21	19.02	21.25	20.42	24.14	26.07	26.20	16.14	310.34
IRL	−0.31	−0.36	−0.36	−0.43	−0.51	−0.56	−0.61	−0.66	−0.70	−0.80	−0.84	−1.01	−1.35	−1.27	−1.21	−10.99
ITA	−7.84	−7.04	−6.82	−8.33	−8.68	−9.14	−9.02	−8.84	−9.83	−10.21	−10.71	−11.07	−11.15	−10.42	−8.65	−137.75
JPN	−31.66	−29.11	−26.19	−22.54	−24.91	−26.41	−25.21	−23.63	−23.68	−26.09	−27.44	−25.96	−24.25	−24.94	−21.93	−383.97
KOR	−6.86	−7.59	−6.97	−4.16	−5.31	−6.15	−6.44	−6.90	−6.93	−7.93	−8.13	−8.97	−9.04	−9.35	−7.25	−107.96
LTU	−0.16	−0.15	−0.18	−0.21	−0.25	−0.30	−0.31	−0.32	−0.37	−0.31	−0.35	−0.39	−0.46	−0.48	−0.36	−4.59
LUX	−0.28	−0.25	−0.26	−0.29	−0.33	−0.26	−0.23	−0.18	−0.21	−0.22	−0.25	−0.23	−0.26	−0.23	−0.21	−3.68
LVA	0.02	−0.04	0.04	0.08	−0.02	−0.02	−0.04	−0.07	−0.08	−0.08	−0.06	−0.13	−0.19	−0.16	−0.04	−0.79
MEX	0.48	−0.72	−0.96	−1.59	−1.93	−2.79	−3.46	−3.99	−3.83	−3.85	−4.26	−4.41	−4.92	−5.11	−3.25	−44.61
MLT	−0.07	−0.07	−0.06	−0.07	−0.08	−0.08	−0.09	−0.08	−0.09	−0.07	−0.08	−0.09	−0.10	−0.09	−0.09	−1.21
NLD	−4.95	−5.08	−4.14	−4.65	−5.46	−5.36	−5.45	−5.39	−5.41	−5.48	−5.72	−5.78	−5.95	−6.28	−5.84	−80.93
POL	−0.88	−1.11	−1.23	−1.65	−1.81	−1.96	−1.97	−1.75	−1.57	−1.81	−2.01	−2.20	−2.54	−2.95	−2.23	−27.68
PRT	−0.79	−0.74	−0.70	−0.86	−1.20	−1.04	−1.14	−1.16	−1.00	−1.34	−1.50	−1.17	−1.45	−1.55	−1.20	−16.84
ROU	0.64	0.59	0.84	0.58	0.73	0.50	0.39	0.55	0.24	0.39	0.42	0.02	−0.41	−0.27	−0.14	5.07
RUS	6.86	5.46	5.38	8.33	14.42	15.41	13.39	11.30	9.61	8.80	6.51	6.22	1.09	−0.67	−1.46	110.65
SVK	0.01	−0.10	−0.06	−0.05	−0.02	−0.09	−0.09	−0.02	−0.18	−0.32	−0.31	−0.36	−0.52	−0.58	−0.62	−3.32
SVN	−0.10	−0.06	−0.06	−0.07	−0.10	−0.06	−0.03	−0.08	−0.17	−0.06	−0.12	−0.04	−0.25	−0.21	−0.12	−1.52
SWE	1.37	0.31	1.50	1.35	1.15	1.29	1.94	0.87	0.02	0.76	1.82	0.98	0.93	1.29	1.26	16.84
TUR	0.92	1.20	1.36	1.33	0.40	−0.61	0.80	0.66	−0.20	−0.27	−0.79	−0.75	−2.04	−5.11	−2.84	−5.95
TWN	−2.66	−3.07	−2.95	−2.56	−2.75	−3.00	−2.75	−2.68	−2.29	−2.83	−2.92	−2.74	−2.30	−2.30	−1.78	−39.57
USA	−27.27	−27.63	−30.83	−38.92	−46.41	−55.59	−56.60	−53.89	−52.52	−56.20	−64.75	−64.19	−56.47	−48.43	−39.57	−719.28
ROW	58.66	59.82	47.44	55.46	64.74	75.09	79.01	77.02	87.42	96.06	103.22	96.11	95.65	91.29	83.73	1170.72

Table B3

World summary: time series (1995–2009) of the complete SDA – for all the seven variables listed in Section 4 – for all countries. The ΔKm^3 and $\Delta\%$ show the cumulative effect with respect to the country-specific water use in the base year (1995).

ISO	IE		T		H		D^*		Q_{CAP}		Q_C		Q_{POP}		Tot	
	ΔKm^3	$\Delta\%$	ΔKm^3	$\Delta\%$	ΔKm^3	$\Delta\%$	ΔKm^3	$\Delta\%$	ΔKm^3	$\Delta\%$	ΔKm^3	$\Delta\%$	ΔKm^3	$\Delta\%$	ΔKm^3	$\Delta\%$
AUS	−12.39	−78.05	−1.40	−8.80	−0.79	−5.00	−0.43	−2.71	11.84	74.57	−1.92	−12.10	2.91	18.30	−2.19	−13.80
AUT	−10.03	−107.75	0.53	5.69	4.68	50.28	0.04	0.46	4.32	46.40	0.69	7.41	0.58	6.20	0.81	8.70
BEL	−0.15	−25.46	−0.04	−6.02	−0.09	−15.24	−0.03	−5.55	0.36	62.13	−0.09	−15.80	0.05	8.47	0.01	2.51
BGR	−1.04	−90.45	0.02	1.71	0.11	9.55	−0.03	−2.59	1.33	115.60	−0.23	−19.72	0.00	0.02	0.16	14.12
BRA	−56.20	−75.37	5.80	7.78	4.83	6.48	2.40	3.22	64.16	86.05	1.58	2.13	15.44	20.71	38.02	50.99
CAN	−55.25	−64.55	3.72	4.35	−13.29	−15.53	1.54	1.80	71.05	83.02	−12.39	−14.48	12.27	14.34	7.65	8.94
CHN	−273.78	−155.22	39.73	22.53	35.32	20.02	39.43	22.36	347.51	197.02	−72.57	−41.14	22.72	12.88	138.36	78.45
CYP	−0.27	−70.81	0.00	0.38	−0.01	−1.49	−0.09	−24.29	0.18	46.39	−0.07	−18.69	0.05	12.64	−0.21	−55.87
CZE	−0.60	−88.88	0.08	12.17	−0.22	−33.16	0.06	8.62	0.73	108.91	0.00	0.55	0.02	3.19	0.08	11.40
DEU	−5.06	−63.85	−0.23	−2.95	0.94	11.82	−0.15	−1.95	3.27	41.28	0.21	2.63	0.33	4.20	−0.70	−8.83
DNK	−0.09	−23.61	−0.02	−6.49	−0.03	−8.24	−0.04	−9.42	0.26	67.66	−0.08	−20.83	0.03	7.88	0.03	6.95
ESP	−5.14	−35.18	0.30	2.04	−2.53	−17.29	0.21	1.44	17.08	116.87	−5.49	−37.59	3.01	20.57	7.43	50.85
EST	−0.02	−104.43	0.00	20.05	0.00	−12.97	−0.06	−312.68	0.02	122.44	0.06	303.25	0.00	0.54	0.00	16.21
FIN	−2.18	−65.68	−0.12	−3.51	−0.23	−6.80	−0.06	−1.94	2.28	68.56	0.05	1.42	0.21	6.38	−0.05	−1.56
FRA	1.86	8.33	−1.03	−4.64	−6.59	−29.57	−0.24	−1.08	10.87	48.77	−9.69	−43.46	1.83	8.19	−3.00	−13.46
GBR	−1.15	−50.87	−0.14	−6.14	−0.29	−12.95	−0.13	−5.53	1.53	67.46	−0.09	−3.93	0.16	7.18	−0.11	−4.77
GRC	−1.60	−32.58	−0.49	−9.87	−2.01	−40.74	−0.11	−2.21	4.25	86.35	−0.84	−17.07	0.31	6.35	−0.48	−9.77
HUN	−0.39	−77.52	0.06	11.63	−0.07	−14.40	−0.02	−4.93	0.55	110.45	−0.12	−23.23	0.01	1.44	0.02	3.44
IDN	−10.21	−74.17	0.14	1.02	2.53	18.37	−0.42	−3.07	8.66	62.94	0.27	1.93	2.84	20.62	3.81	27.65
IND	−159.15	−65.82	4.95	2.05	−48.35	−19.99	3.35	1.39	305.68	126.42	−100.01	−41.36	56.55	23.39	63.03	26.07
IRL	−0.20	−54.21	0.03	6.93	−0.09	−23.41	0.01	3.18	0.35	95.14	−0.06	−16.35	0.06	17.58	0.11	28.86
ITA	−8.95	−60.44	−0.09	−0.61	1.55	10.48	−0.19	−1.29	10.18	68.76	−0.90	−6.09	1.05	7.06	2.65	17.87
JPN	−0.20	−0.86	−1.48	−6.28	0.51	2.18	−0.96	−4.07	−1.01	−4.28	0.05	0.23	0.72	3.06	−2.37	−10.03
KOR	−0.90	−49.03	0.11	6.08	0.35	18.88	−0.10	−5.30	1.15	62.41	−0.55	−29.94	0.20	11.16	0.26	14.26
LTU	−0.17	−115.48	0.02	12.65	−0.06	−37.59	0.01	5.51	0.21	140.91	0.00	−3.21	0.00	−3.35	0.00	−0.57
LUX	−0.04	−126.63	0.01	31.69	0.01	14.73	0.01	15.60	0.02	71.32	0.00	−6.00	0.01	14.85	0.01	15.57
LVA	−1.25	−168.25	0.15	19.71	−0.02	−2.11	0.04	6.04	1.19	159.38	0.06	7.61	−0.04	−5.90	0.12	16.48
MEX	−23.95	−116.44	0.10	0.46	1.46	7.09	0.40	1.94	20.79	101.04	−1.04	−5.05	4.29	20.87	2.04	9.91
MLT	−0.01	−89.72	0.00	2.59	0.00	2.49	0.00	−1.93	0.01	31.40	0.00	0.60	0.00	7.49	−0.01	−47.09
NLD	−0.34	−44.24	0.00	0.03	−0.08	−10.89	0.05	6.00	0.44	57.06	−0.12	−15.04	0.06	7.52	0.00	0.45
POL	−1.33	−91.53	0.20	13.94	−0.31	−21.13	0.23	15.53	2.19	151.33	−0.27	−18.73	0.03	2.01	0.75	51.43

(*continued on next page*)

Table B3 (*continued*)

ISO	IE		T		H		D^*		Q_{CAP}		Q_C		Q_{POP}		Tot	
	ΔKm^3	Δ%	ΔKm^3	Δ%	ΔKm^3	Δ%	ΔKm^3	Δ%	ΔKm^3	Δ%	ΔKm^3	Δ%	ΔKm^3	Δ%	ΔKm^3	Δ%
PRT	−3.34	−75.39	−0.03	−0.66	−0.02	−0.51	−0.19	−4.40	3.19	72.20	−0.54	−12.15	0.34	7.67	−0.59	−13.25
ROU	−7.74	−142.76	0.18	3.30	−0.51	−9.47	0.32	5.88	8.09	149.13	−0.49	−9.09	−0.08	−1.47	−0.24	−4.48
RUS	−61.54	−109.79	3.99	7.12	−8.62	−15.37	−0.86	−1.54	76.10	135.78	−3.75	−6.70	−0.18	−0.32	5.14	9.17
SVK	−2.08	−148.22	0.11	7.90	−0.22	−15.45	0.10	7.28	1.65	117.71	0.26	18.79	0.03	2.45	−0.13	−9.52
SVN	−0.52	−60.65	−0.02	−1.97	0.13	14.83	0.01	0.78	0.73	85.35	−0.01	−0.89	0.05	5.50	0.37	42.95
SWE	−10.38	−61.53	−0.55	−3.29	0.77	4.56	−0.37	−2.20	8.48	50.29	0.42	2.47	1.07	6.36	−0.56	−3.34
TUR	−28.96	−126.49	1.06	4.65	4.29	18.75	1.02	4.46	23.40	102.20	−3.52	−15.36	4.58	20.02	1.88	8.22
TWN	2.08	34.01	−0.81	−13.20	−0.49	−7.98	−0.69	−11.25	1.86	30.46	−2.01	−32.88	0.53	8.73	0.48	7.90
USA	−86.57	−49.42	−2.60	−1.48	−18.35	−10.48	−4.92	−2.81	97.98	55.93	−3.42	−1.95	25.00	14.27	7.12	4.07
ROW	−537.16	−110.81	5.05	1.04	177.73	36.67	11.82	2.44	384.36	79.29	−10.62	−2.19	125.50	25.89	156.67	32.32

Table B4

World Sectoral summary: time series (1995–2009) of the SDA for all countries and for the three main macro-sectors: *AFF*, *EWG*, and *DUS*. Δ96 means the total variation in *VW* (Km^3) from 1995 to 1996 in the specific sector; the same reasoning holds true for Δ01 (2001-2000) and Δ09 (2009-2008). The ΔKm^3 and Δ% state for the cumulative effect with respect to the country-specific water use in the base year (1995).

ISO	*AFF*					*EWG*					*DUS*				
	Δ96	Δ01	Δ09	$\Delta TOT(Km^3)$	$\Delta TOT(\%)$	Δ96	Δ01	Δ09	$\Delta TOT(Km^3)$	$\Delta TOT(\%)$	Δ96	Δ01	Δ09	$\Delta TOT(Km^3)$	$\Delta TOT(\%)$
AUS	0.81	0.92	1.44	−1.30	−8.17	−0.12	0.05	0.08	−0.90	−5.64	0.00	0.00	−0.01	0.00	0.01
AUT	0.00	0.00	−0.01	−0.01	−0.15	−0.70	−0.40	0.59	0.79	8.48	0.00	0.00	−0.01	0.03	0.36
BEL	0.00	−0.01	0.00	−0.01	−1.26	−0.02	0.00	−0.02	0.00	−0.42	0.00	0.00	−0.01	0.02	4.20
BGR	−0.08	−0.01	−0.02	−0.15	−13.03	0.15	−0.23	0.16	0.28	24.69	−0.03	0.00	−0.02	0.03	2.47
BRA	−1.44	−0.19	0.22	4.40	5.90	2.90	−9.01	5.25	33.56	45.02	0.01	−0.01	−0.04	0.05	0.07
CAN	0.09	−0.17	−0.17	0.19	0.22	4.83	−6.17	−2.56	6.84	7.99	0.03	0.01	0.04	0.62	0.73
CHN	7.60	−4.10	1.49	19.09	10.83	−0.64	13.47	7.46	104.07	59.01	0.52	0.46	2.54	15.20	8.62
CYP	−0.06	−0.07	0.00	−0.21	−55.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
CZE	0.00	0.00	0.00	−0.04	−6.37	−0.01	0.07	0.10	0.10	15.55	0.00	0.00	−0.01	0.01	2.22
DEU	0.01	−0.02	−0.01	0.00	−0.01	0.04	0.25	−0.56	−0.76	−9.65	−0.01	0.00	−0.30	0.07	0.83
DNK	0.00	0.01	0.00	0.03	7.76	0.00	0.00	0.00	0.00	−0.71	0.00	0.00	0.00	0.00	−0.11
ESP	5.40	0.21	0.65	6.58	45.01	4.09	2.81	0.69	0.79	5.39	0.00	0.01	−0.01	0.07	0.45
EST	0.00	0.00	0.00	−0.01	−29.56	0.00	0.00	0.00	0.01	39.43	0.00	0.00	0.00	0.00	6.34
FIN	0.00	0.00	0.00	−0.01	−0.16	−0.26	−0.36	−1.08	−0.06	−1.76	0.00	0.00	−0.01	0.01	0.36
FRA	0.22	0.05	0.08	0.39	1.73	−1.67	1.84	−1.62	−3.87	−17.34	0.00	0.02	−0.11	0.48	2.14
GBR	0.02	−0.04	−0.01	−0.17	−7.47	−0.35	−0.25	0.02	0.10	4.58	0.00	0.00	−0.02	−0.04	−1.89
GRC	0.01	0.08	−0.29	−0.93	−18.97	0.20	−0.39	0.50	0.45	9.17	0.00	0.00	0.00	0.00	0.03
HUN	0.01	0.03	−0.04	−0.03	−6.21	0.01	0.00	0.00	0.02	3.19	0.00	0.00	−0.06	0.03	6.47
IDN	0.26	−0.21	0.91	2.85	20.74	0.15	0.40	−0.04	0.94	6.85	0.00	0.00	0.00	0.01	0.05
IND	4.19	−4.28	−10.02	52.97	21.91	−0.90	−0.19	−1.81	8.40	3.47	0.07	0.05	0.14	1.66	0.69
IRL	0.00	0.00	0.00	0.01	3.44	0.00	−0.06	−0.02	0.05	12.52	0.00	0.00	0.01	0.05	12.91
ITA	0.18	−0.07	−0.15	−0.10	−0.65	1.04	0.64	1.84	2.78	18.78	0.00	0.01	−0.09	−0.04	−0.25
JPN	−0.10	−0.09	−0.08	−0.51	−2.18	−0.39	−0.76	−0.31	−1.70	−7.18	0.01	−0.02	−0.09	−0.16	−0.68
KOR	0.09	0.03	0.04	0.17	9.06	−0.08	0.03	−0.06	0.01	0.71	0.01	0.01	0.00	0.08	4.49
LTU	0.00	−0.01	0.00	−0.01	−9.22	−0.01	0.00	0.01	0.01	8.46	0.00	0.00	0.00	0.00	0.20
LUX	0.00	0.00	0.00	0.00	1.80	−0.01	0.00	−0.01	0.00	12.62	0.00	0.00	0.00	0.00	1.15
LVA	0.00	0.00	0.00	−0.01	−0.91	−0.26	0.00	0.09	0.13	17.09	0.00	0.00	0.00	0.00	0.30
MEX	1.31	0.81	−1.19	2.19	10.64	0.96	−1.13	−3.05	−0.20	−0.97	0.03	−0.02	−0.03	0.05	0.24
MLT	0.00	0.00	0.00	−0.01	−47.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
NLD	0.00	−0.01	0.01	−0.04	−4.73	0.00	−0.01	0.00	0.00	0.32	0.00	0.00	−0.01	0.04	4.86
POL	−0.02	0.02	−0.03	0.01	0.76	0.01	0.05	0.05	0.12	8.24	0.02	0.03	−0.07	0.61	42.42
PRT	0.21	−0.12	−0.17	−0.58	−13.14	1.57	0.66	0.36	−0.01	−0.33	0.00	0.00	−0.01	0.01	0.22
ROU	−0.17	0.27	−0.09	−0.02	−0.40	−0.23	0.04	−0.41	−0.28	−5.23	0.01	0.01	0.00	0.06	1.15
RUS	−0.68	0.53	−3.26	5.13	9.15	−5.41	2.40	2.31	−0.30	−0.54	−0.28	0.06	−0.31	0.31	0.56
SVK	0.02	0.03	−0.02	−0.01	−0.84	−0.16	0.08	0.08	−0.13	−8.93	0.00	0.00	−0.01	0.00	0.25
SVN	0.00	0.00	0.00	0.00	−0.43	0.10	−0.01	0.17	0.36	42.01	0.00	0.00	−0.01	0.01	1.37
SWE	0.00	0.00	0.00	−0.02	−0.15	−4.01	0.12	−0.79	−0.55	−3.27	0.00	0.00	−0.01	0.01	0.07
TUR	0.48	−0.95	0.27	1.56	6.80	1.21	−1.68	0.66	0.10	0.45	0.00	0.00	−0.04	0.22	0.97
TWN	0.21	−0.21	−0.72	0.40	6.62	−0.02	0.13	−0.14	−0.27	−4.37	0.00	−0.02	−0.13	0.35	5.65
USA	7.07	−0.13	2.83	17.73	10.12	9.01	−15.90	4.62	−9.43	−5.38	0.12	−0.50	−1.02	−1.18	−0.67
ROW	3.51	9.04	14.20	106.91	22.05	−2.59	−1.27	−0.10	47.52	9.80	0.37	0.12	0.00	2.25	0.46

Table B5
Fundamental properties – for all years – of *BVWION* for all intermediate exchanges (Ω) and for international trade only (right panel). The *VWT* % is computed with respect to the overall *BVW*, while *VWT*% (Ω) refers to the share computed with respect to the *BVWION*.

Year	All Trade Ω				International Trade				
	$VWTKm^3$	*VWT*%	n. links	density	$VWTKm^3$	*VWT*% (Ω)	*VWT*%	n. links	density
1995	621.0	41.00%	99864	5.10%	25.8	4.16%	1.71%	90847	4.75%
1996	639.5	41.17%	101224	5.16%	26.5	4.14%	1.71%	92189	4.82%
1997	659.4	41.67%	105820	5.40%	31.8	4.82%	2.01%	96776	5.06%
1998	653.1	41.43%	106864	5.45%	28.9	4.42%	1.83%	97834	5.12%
1999	658.0	40.94%	107124	5.47%	30.1	4.58%	1.87%	98056	5.13%
2000	662.7	41.18%	110121	5.62%	33.8	5.11%	2.10%	101016	5.29%
2001	655.5	41.07%	110122	5.62%	32.3	4.93%	2.02%	101015	5.29%
2002	650.9	40.34%	111393	5.68%	28.0	4.30%	1.73%	102247	5.35%
2003	667.6	40.85%	112592	5.74%	27.3	4.08%	1.67%	103463	5.41%
2004	716.8	41.49%	115694	5.90%	29.9	4.17%	1.73%	106545	5.58%
2005	742.0	41.59%	116685	5.95%	30.0	4.05%	1.68%	107503	5.63%
2006	775.2	42.15%	120495	6.15%	32.4	4.17%	1.76%	111314	5.82%
2007	803.5	42.40%	121625	6.21%	33.2	4.13%	1.75%	112453	5.88%
2008	831.1	43.23%	122911	6.27%	35.3	4.24%	1.84%	113739	5.95%
2009	830.9	42.81%	118018	6.02%	32.2	3.88%	1.66%	108904	5.70%

Table B6
Sectoral classification in WIOD (based on Statistical classification of economic activities in the European Community (NACE) rev 1.1). See Ref. [61] for a detailed description.

ID	Description	NACE codes
Atb	Agriculture, Hunting, Forestry and Fishing	01, 02, 05
C	Mining and Quarrying	10, 11, 12, 13, 14
Fb	Food, Beverages and Tobacco	15, 16
Tx	Textiles and Textile Products	17, 18
19	Leather, Leather and Footwear	19
20	Wood and Products of Wood and Cork	20
Pp	Pulp, Paper, Paper, Printing and Publishing	21, 22
23	Coke, Refined Petroleum and Nuclear Fuel	23
CH	Chemicals and Chemical Products	24
25	Rubber and Plastics	25
OMet	Other Non-Metallic Mineral	26
Met	Basic Metals and Fabricated Metal	27, 28
29	Machinery, Nec	29
30t33	Electrical and Optical Equipment	30, 31, 32, 33
34t35	Transport Equipment	34, 35
36t37	Manufacturing, Nec; Recycling	36, 37
EWG	Electricity, Gas and Water Supply	40, 41
F	Construction	45
50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles	50
51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	51
52	Retail Trade, Repair of Household Goods	52
H	Hotels and Restaurants	55
60	Other Inland Transport	60
61	Other Water Transport	61
62	Other Air Transport	62
63	Other Supporting and Auxiliary Transport Activities	63
64	Post and Telecommunications	64
J	Financial Intermediation	65, 66, 67
70	Real Estate Activities	70
71t74	Renting of Machinery and Equipment and Other Business Activities	71, 72, 73, 74
L	Public Admin and Defence; Compulsory Social Security	75
M	Education	80
N	Health and Social Work	85
O	Other Community, Social and Personal Services	90, 91, 92, 93
P	Private Households with Employed Persons	95
HH	Households	HH

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